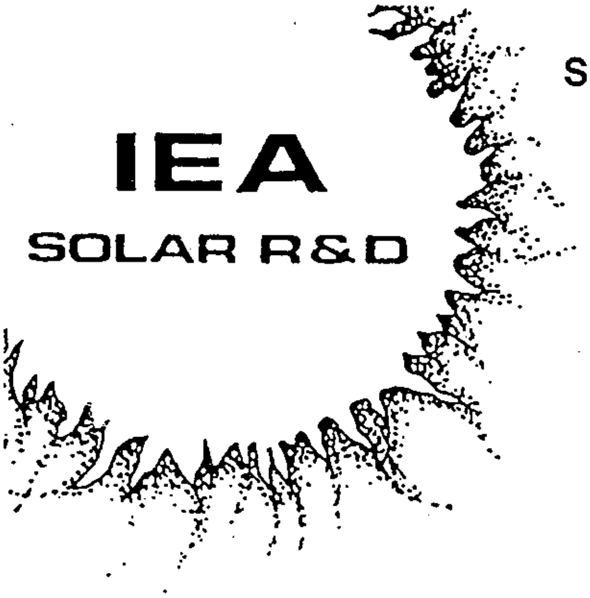


INTERNATIONAL ENERGY AGENCY
SOLAR HEATING & COOLING - TASK XI

Passive and Hybrid Solar Commercial Buildings

Advanced Case Studies Seminar

24th April 1991

IEA
SOLAR R&D

INTERNATIONAL ENERGY AGENCY
SOLAR HEATING & COOLING - TASK XI

Passive and Hybrid Solar Commercial Buildings

Advanced Case Studies Seminar

April 1991

Countries participating in Task XI :

Austria
Belgium
Canada
Denmark
European Communities
Finland
Germany
Italy
Norway
Spain
Sweden
Switzerland*
United Kingdom
United States

* Operating Agent

PREFACE

IEA XI : ADVANCED CASE STUDIES

Researchers in participating countries of the IEA Task XI of the Solar Heating and Cooling Programme have been studying real buildings which employ passive and hybrid passive/active solar strategies designed to reduce use of non-renewable fuels.

The basic strategies used to achieve this end have been divided into four categories, the first three being, **HEATING**, **COOLING** and **LIGHTING**. The fourth category is dedicated to the increasingly popular **ATRIUM** which often provides a combination of passive heating, cooling and lighting.

The buildings studied cover a wide range of climates, building types and solar strategies, varying from a day care centre in Norway, which uses a direct gain atrium for heating, to a naturally cooled exhibition building in Spain. In-between these two are an assortment of offices, educational buildings and sports halls.

Many of these buildings have been previously reported as Basic Case Studies in which brief reports of the building were given. Those Basic Case Studies gave a wide range of information but not at a detailed level. The intention of this collection of Advanced Case Studies is to report specific research findings in greater depth and address the more detailed performance aspects of the solar design.

The studies brought together here report findings of research carried out in more than 20 buildings. The studies deal with many aspects of solar design, as used in commercial buildings, and represent all of the four strategies.

As a contribution to the understanding of passive solar design these papers represent the findings of some of the foremost researchers of Europe. The papers which result from this combination provide a wealth of information which will do much to advance passive solar design.

Copies of the Basic Case Studies book can be obtained from :

The Renewable Energy Promotion Department (REPD)
Energy Technology Support Unit
Harwell Laboratory
Oxfordshire
OX11 ORA

CONTENTS

INTRODUCTION TO THE INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA) was formed in November 1974 to establish cooperation among a number of industrialised countries in the vital area of energy policy. It is an autonomous body within the framework of the Organisation for Economic Cooperation and Development (OECD). Twenty one countries are presently members, with the Commission of the European communities also participating in the work of the IEA under a special arrangement.

One element of the IEA's programme involves cooperation in the research and development of alternative energy resources in order to reduce excessive dependence on fossil fuels. A number of new and improved energy technologies which have the potential of making significant contribution to global energy needs were identified for collaborative efforts. The IEA committee on Energy Research and Development (CRD), comprising representatives from each member country, supported by a small Secretariat staff, is the focus of IEA RD & D activities. Four Working Parties (in Conservation, Fossil Fuels, Renewable Energy, and Fusion) are charged with identifying new areas for cooperation and advising the CRD on policy matters in their respective technology areas.

IEA SOLAR HEATING AND COOLING PROGRAMME

Solar Heating and Cooling was one of the technologies selected for joint activities. During 1976-77, specific projects were identified in key areas of this field and a formal Implementing Agreement drawn up. The Agreement covers the obligations and rights of the Participants and outlines the scope of each project or "task" in annexes to the document. There now eighteen signatories to the Agreement:

Australia
Austria
Belgium
Canada
Denmark
Commission of the European Communities
Finland
Germany
Italy
Japan
Netherlands
New Zealand
Norway
Spain
Sweden
Switzerland
United Kingdom
United States

The overall programme is managed by an Executive Committee, while the management of the individual tasks is the responsibility of the Operating Agents. The tasks of the IEA Solar Heating and Cooling Programme and their respective Operating Agents are as follows:-

Task I	Investigation of the Performance of Solar Heating and Cooling Systems - Technical University of Denmark.
Task II	Coordination of Research and Development on Solar Heating and Cooling - Solar Research Laboratory - GIRIN, Japan.
Task III	Performance Testing of Solar Collectors - University College, Cardiff, UK.
Task IV	Development of an Insulation Handbook and Instrument Package - US Department of Energy.
Task V	Use of Existing Meteorological Information for Solar Energy Application - Swedish Meteorological and Hydrological Institute.
Task VI	Performance of Solar Heating, Cooling and Hot Water Systems Using Evacuated Collectors - US Department of Energy.
Task VII	Central Solar Heating Plants with Seasonal Storage - Swedish Council for Building Research.
Task VIII	Passive and Hybrid Solar Low Energy Buildings - US Department of Energy.
Task IX	Solar Radiation and Pyranometry Studies - KFA Julich, FRG.
Task X	Solar Materials Research and Development - AIST, MITI, Japan.
Task XI	Passive Solar Commercial Buildings - Swiss Federal Office of Energy.
Task XII	Solar Building Analysis and Design Tools - US Department of Energy.
Task XIII	Advanced Solar Low-Energy Buildings - Royal Ministry of Petroleum and Energy, Norway.

TASK XI : PASSIVE AND HYBRID SOLAR COMMERCIAL BUILDINGS

Growing interest in the energy savings opportunities presented by the use of passive solar concepts in commercial buildings prompted members of the IEA Solar Heating and Cooling Programme to form a new task in 1985. At that time much of the national and international research into passive solar, energy efficient building design had concentrated on residential buildings. Task XI was an early recognition of the enormous potential for energy savings through the application of passive solar techniques to displace fuel used for heating, cooling and lighting in commercial buildings.

These buildings differ markedly from residences in much more than size. The variety of building forms, HVAC systems, controls, internal loads, occupancy profiles and schedules, and special user requirements is made more complex by their interactions. Furthermore, there is still relatively little experience of utilising passive solar techniques to save energy in commercial buildings.

Task XI was structured to optimise the contributions, and national programmes, of the participating nations. It comprises three linked sub tasks:

A Case Studies : led by the UK
B Simulation : led by the USA
C Design Information : led by CH

These proceedings are a product of Sub Task A and brings together detailed information (through simulation and monitoring) of 22 passive solar commercial buildings, spanning a wide variety of climates. Sub Task A has also published a collection of Basic Case Studies in which basic information from 48 buildings is presented in a standardised format.

In order to complete Task XI the wide variety of case study material will be drawn together along with the results of simulation studies (Sub Task B) to generate a sourcebook providing a comprehensive set of information for designers (Sub Task C). Thus the annexe is looking forward to the next generation of low energy commercial buildings which make effective use of the sun to displace space heating (& cooling) and to displace electric lighting.

ADVANCED CASE STUDIES

DAYLIGHTING SECTION

DAYLIGHTING THROUGH ROOFLIGHTS
IN THE BRF HEADQUARTERS

March 1989
Esbensen, Consulting Engineers
41 Havnegade
DK-1058 Copenhagen K

Preface

There exists a large potential for energy savings by the careful utilization of daylight instead of electric light
when designing commercial and institutional buildings: The owner of the building can obtain considerable savings on the expenses for energy, and at the same time the peak load of the power plants will be reduced.

This report describes the results from the investigation of daylighting in the BRF Headquarters, which is a recently built large Danish office building owned by BRF (Byggeriets Realkredit Fond). The building was designed by architect Gunnar Gundersen from KHR A | S, Architects & Planners. Jørgen K. Andersen and Gunnar Ø. Sørensen from Birch & Krogboe K/S were consulting engineers.

The main daylighting feature of the building is the circulation spaces, which are lit by rooflights. Furthermore, the electric lighting is automatically controlled according to the available daylight.

The investigation of the building is an "Advanced Case Study" in relation to TASK XI of the Solar Heating and Cooling program under the International Energy Agency (IEA).

The work described in this report was sponsored by the Danish Ministry of Energy, and it was carried out in 1988 by Ph.D. Casper Paludan-Müller and Poul E. Kristensen from Esbensen, Consulting Engineers.

The thermal Insulation Laboratory, Technical University of Denmark has participated in the planning of the project, and supplied the monitoring equipment for the monitoring programme.

Thanks are offered to the technical staff at BRF for their considerable assistance.

Abstract

The circulation area of the three floors of a recently built 17000 m^2 Danish office building is lit by means of rooflights. Electrical lighting is automatically turned on/off depending on the exterior illuminance. An investigation has been carried out in order to evaluate the electricity savings due to the daylighting.

The study includes detailed measurements concerning the lighting. During three weeks, data collection has continuously been carried out for the exterior and the interior illuminance, and the status of the electrical lighting. Daylight Factors and optical characteristics have been measured.

The building has been modelled by means of the computer program DAYLITE. Measured and predicted Daylight Factors are compared. The yearly electricity savings due to the lighting strategy are calculated, and parametric studies are carried out.

The measurements and calculations indicate a very good performance of the daylighting system.

1. INTRODUCTION

1.1. Background

The BRF Headquarters is the office building of a Danish financing institute for property mortgages ("Byggeriets Realkredit Fond"). It is situated in Lyngby, 10 km north of Copenhagen city. The building was finished in 1986, and it is now the place of work for about 600 people. The building has four storeys and the gross floor area is 19620 m^2.

At the planning of the design of the new building, it was emphasized by the client that lighting should largely be provided by daylight instead of electric light. As a consequence, the use of central overglazed spaces is a dominant feature of the building.

The purpose of this study has been to analyse the benefits that are obtained by use of the rooflights. As an immediate impression, the provision of daylight to the rooms creates a pleasant atmosphere. In addition to that, the replacement of artificial light with daylight results in savings of electric energy.

The amount of saved energy is determined by means of detailed calculations, and the connection between the savings and different important parameters is investigated. Thus from this "case study" of the BRF Headquarters, useful informations are gained for future projects concerning the use of similar daylighting strategies.

1.2. Building description

In this section is given a brief description of the BRF Headquarters, the main stress being laid on the central overglazed rooms. A more detailed description was previously carried out within the IEA, task XI programme [1].

General

Figure 1.1. shows a photo of the building. It consists of a four-storeyed main building and three four-storeyed office blocks. The four sections of the building are linked together. All of the sections have a glass covered central room for circulation. In the main building there is a quadratic shaped atrium, and in the office blocks there are arcade rooms, stretching lengthwise between the two ends of the block.

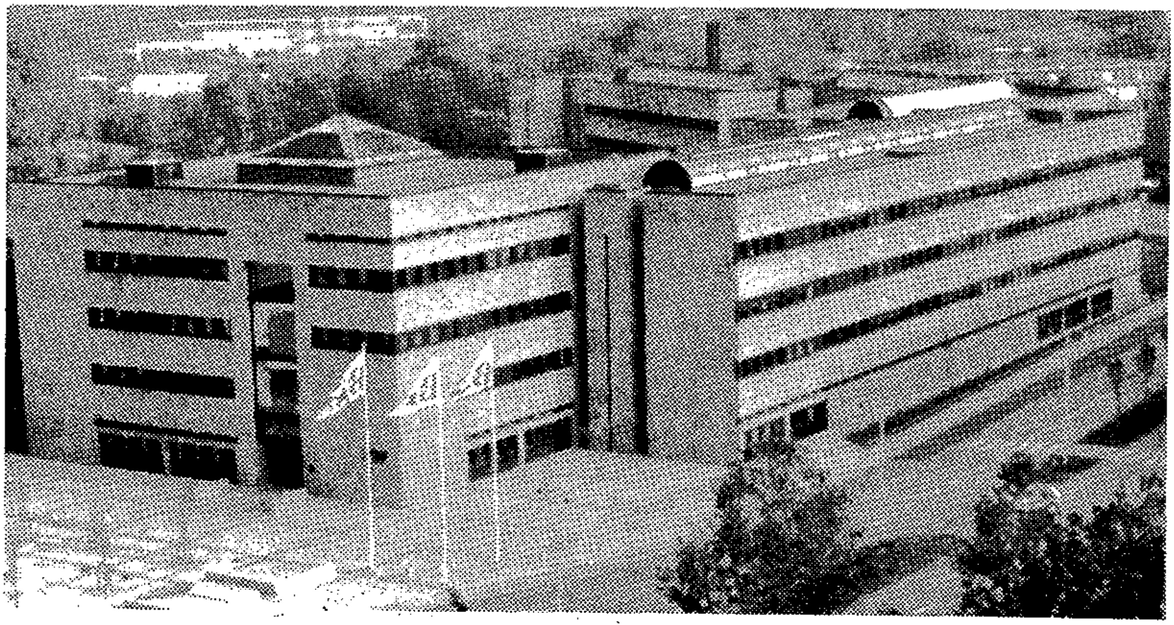


Fig. 1.1. The BRF Headquarters.

Figure 1.2. shows the plan of one of the floors. The atria are open through the 1st, 2nd and 3rd floor, whereas there is no access of daylight to the circulation area of the ground floor. The offices receive daylight through the windows in the facades. There are no windows between the offices and the atria.

Of the 19620 m^2 floor area, 10112 m_2 (52%) is "net area", i.e. it belongs to offices and rooms for meetings. The circulation area is 5810 m^2 (30%), toilets and cloakrooms are 1048 m^2 (5%), and service area amounts to 2650 m^2 (13%). The gross height of the stories is 4.5 m for the ground floor and 3.6 m for the first, second and third floor.

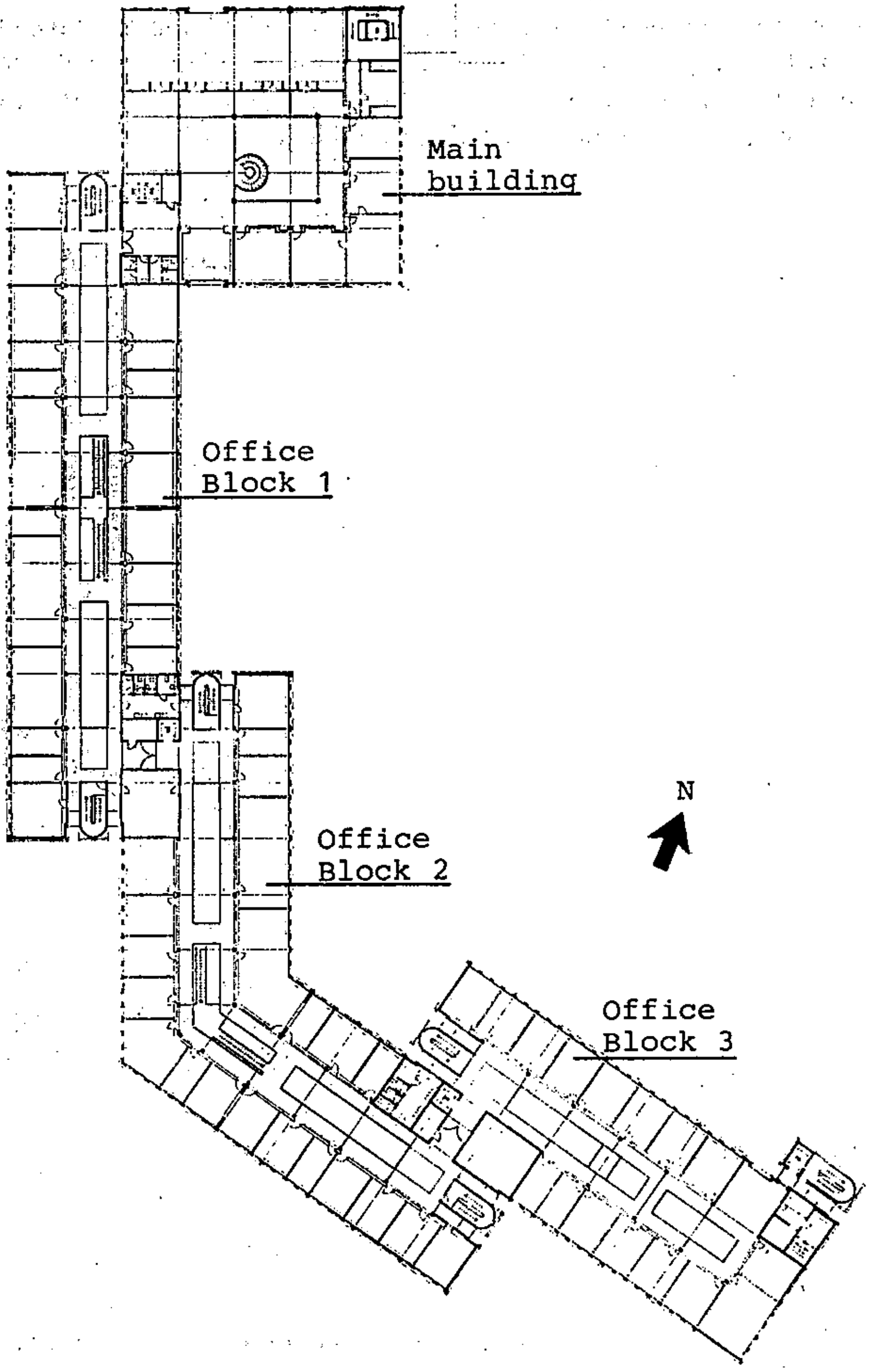


Fig. 1.2. Plan of the third floor of the building. The screened area represents the circulation area.

Characteristics of the arcade rooms

Figure 1.3. shows a photo of the glass covered circulation area, as it appears from the top floor of one of the office blocks. The geometry of the atrium appears from figure 1.4. The total height of the room is 13.2 m. The width of the room is 6.5 m between the walls, and at the level of the horizontal divisions it is 3.0 m.

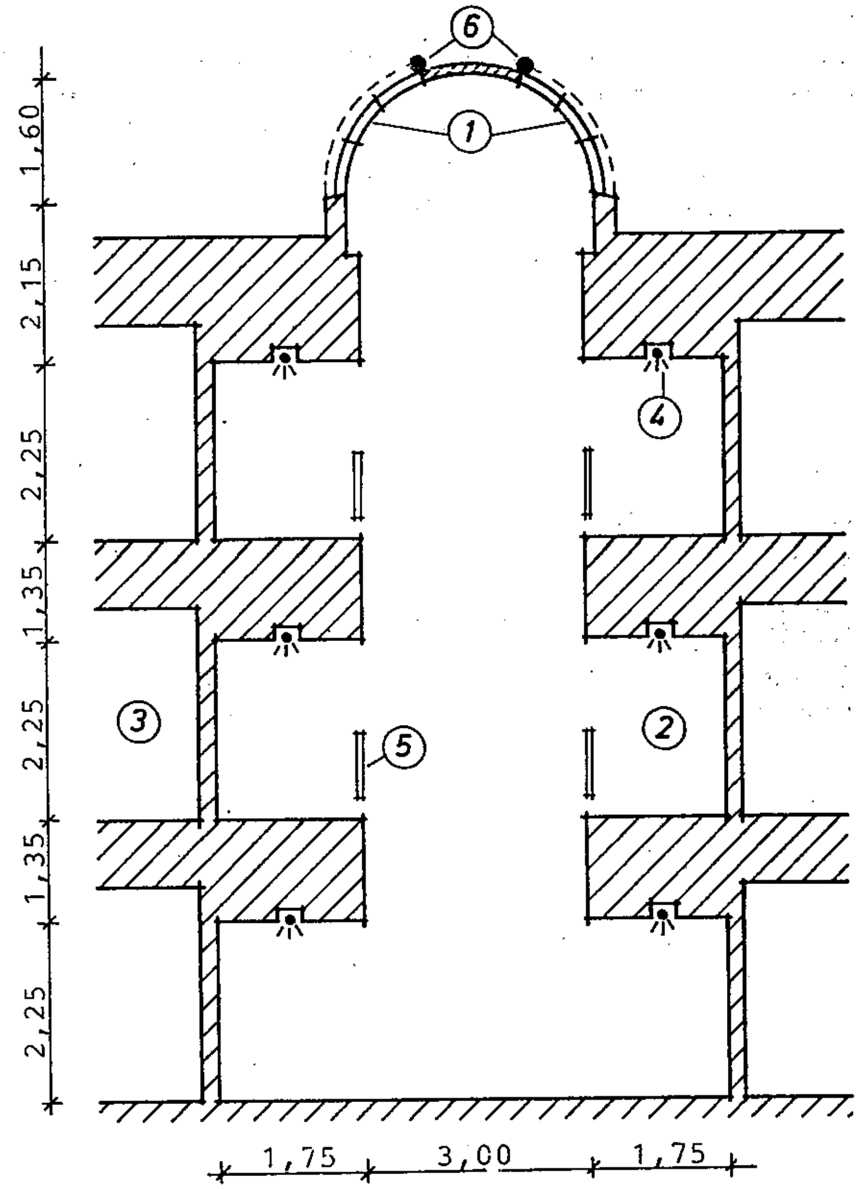
In the rooflights there are placed 3.9 m^2 of windows per m in the longitudinal direction of the building. The transparent part of the windows amounts to 85% of the area. They have two layers of 4 mm normal float glass. The rooflights are not subjected to shading by any surrounding buildings.

The ceiling over the corridors and the vertical walls of the divisions are painted white. The wall surfaces have a slightly toned white colour, and the wooden flooring has a relatively dark brown colour. The railings along the corridors, the staircases and the crossings have transparent acrylic plates as fencing, and thus they have no considerable influence on the light distribution.

All floors of the arcade room were originally meant to function as circulation area. However, it has later been decided to use the first floor in two of the blocks for files, and at these locations a large part of the wall area is covered with shelves. Apart from that, there are no furniture or other obstructions.

The desired illuminance on the circulation area is 50 - 100 lux. The electric lighting is controlled by an energy manage-ment system, using a light sensor placed on the roof, so that the desired minimum value is kept during the working hours. The lighting is controlled individually for each floor. The control does not include the areas at the files on the first floor and some relatively dark areas at the connections between the blocks, where the lighting is on during the whole day.

Fig. 1.3. The glass covered circulation area of the office blocks.



1. Rooflights (two layers of glass).
2. Corridors for circulation.
3. Offices on each side of the room
4. Position of electric lifhting.
5. Transparent acrylic plates as fencing.
6. Exterior blinds.

Fig. 1.4. Characteristics of the three-storeyed arcade rooms. (The dimensions are in m.)

The light is automatically turned off between 6.15 p.m. and 5.15 a.m. and during the weekends, but it is possible to turn it on manually. It is due to the arrival of the cleaning staff that lighting is required so early in the morning.

The electric lighting is provided by efficient fluorescent tubes, placed in the ceiling of the corridors. The lighting power density at the floors of the corridors is 7.8 W/m^2.

Exterior blinds are mounted at the top of the rooflights in order to prevent overheating due to excess solar radiation. By use of the blinds, visual discomfort (because of glare) is also prevented. The activation of the blinds is controlled automatically by the use of light sensors. (There are individual sensors for each of the four orientations of the roof light windows). Figure 1.5. shows the blinds in function.

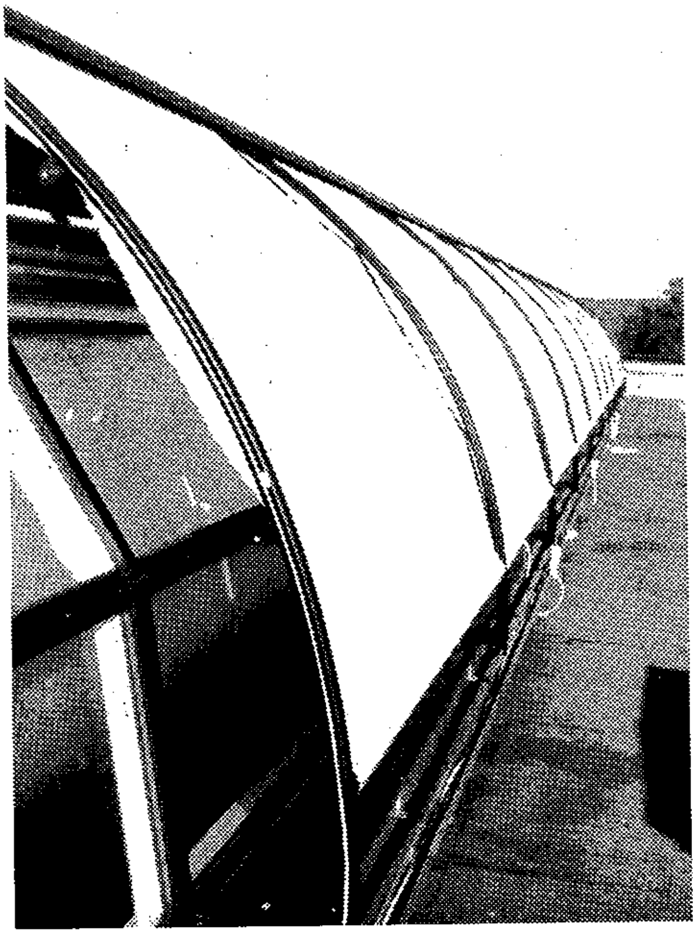


Fig. 1.5. Blinds for control of excess solar radiation.

2. MEASUREMENTS

2.1. General

Measurements of the lighting conditions in the arcade rooms took place during about three weeks from the middle of September till the beginning of October. During most of this period, continuous data collection was carried out. Separate measurements of different characteristic parameters took place within two to three days. The measurement equipment was installed in block 3 (the position of the block is shown on figure 1.2.). The facades of this block are facing almost directly north and south (the azimuth is 5°).

2.2. Data acquisition

During the two weeks of data collection the following quantities were continuously measured:

- The total exterior illuminance on the horizontal plane.
- The total interior illuminance on horizontal at a specific point on one of the floors.
- Status (on/off) of the electric lighting on all three floors.
- Status (up/down) of the movable sunblinds in front of the rooflights.

Three "systems" were used for the data acquisition:

- The illumination data and the status of the electric lighting on the actual floor (where the illuminance is measured) were collected by a portable datalogger (GRANT SQURRIEL). The three channels vere scanned every ten minutes.
- A pen recorder with two channels (KIPP & ZONEN BD 9) was used for registering the times when the motors of the north- and southfacing blinds were activated.
- For each day, the duration of the electrical lighting on all three floors was registered by the energy management system of the building

The data acquisition system with the datalogger and the pen recorder is shown on figure 2.1.

Two luxmeters with photo cell sensors (GOSSEN MAVOLUX) were used for measuring the exterior and interior illuminance. The outdoor measuring probe was mounted on a stand on the roof as shown on figure 2.2. The indoor measuring probe was placed one meter above the floor and 0.60 m from the side wall of the corridor. The positions of the indoor measuring points were regarded as "representative", i.e. they were not close to the staircases and the crossings, that are causing some shading on the underlying areas.

A relation between the illuminance at the chosen points, and the illuminance at other locations is obtained from detailed measurements of the Daylight Factor. According to the specifications for the luxmeter and the datalogger, the total accuracy is within 300 lux + 5% of the measured value for the outdoor illuminance and 3 lux + 5% of the measured value for the indoor illuminance.

In addition to the data collection, observations were made concerning the nature of the weather for the individual days.

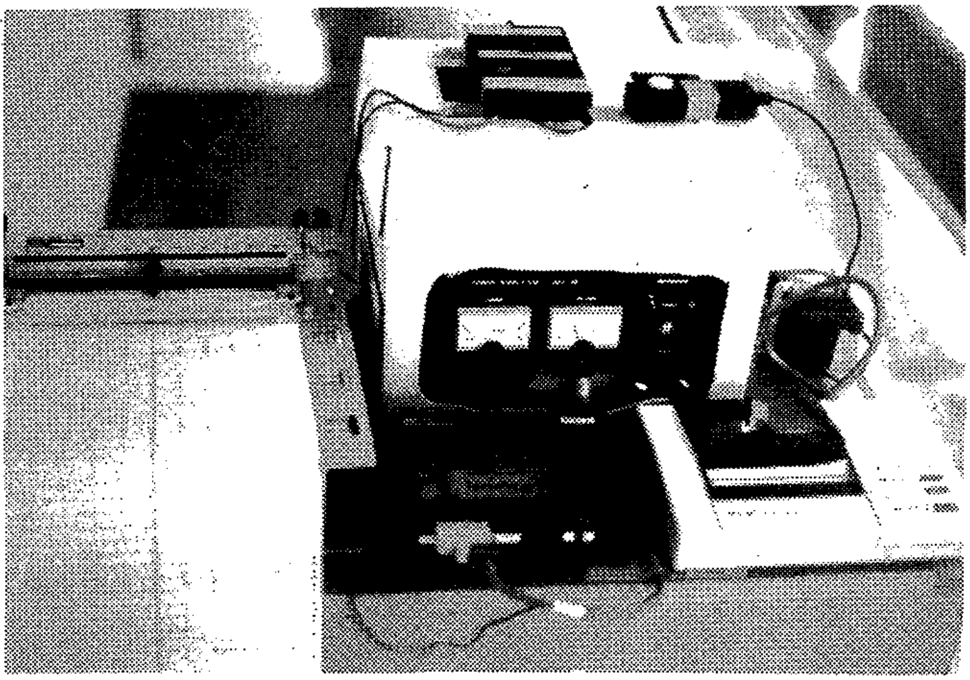


Fig. 2.1. The data acquisition system.

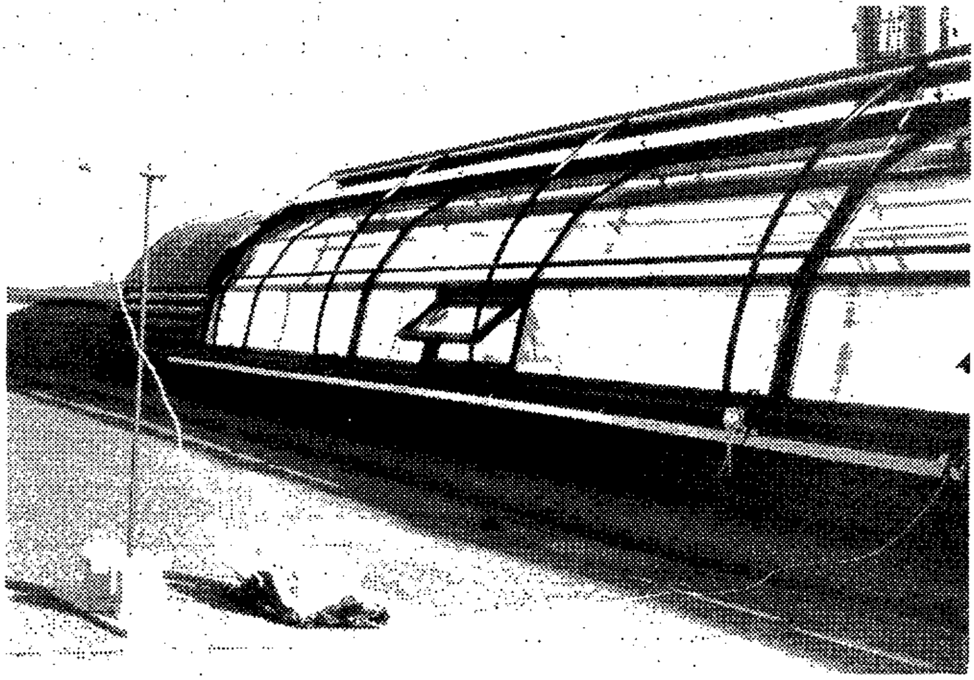


Fig. 2.2. Position of the outdoor measuring probe on the roof.

2.3. Results

2.3.1. Main results for the whole period

From the measuring period ten days with complete data were chosen. No Saturdays or Sundays were included, thus the ten days represent two working weeks. The length of the "working day" is 13 hours, from about 5.15 a.m. to about 6.15 p.m. (The times given are approximate solar time for the period).

For each of the ten days the following principal results are shown in table 2.1.

- An indication of the dominant nature of the cloud cover during the day.
- The mean value $E_{mean\ g,h}$ and the maximum value $E_{max\ g,h}$ of the exterior global illuminance $E_{g,h}$ on horizontal during the hours from sunrise to sunset.
- The fraction of the working day during which the blinds of the southfacing part of the rooflights were down. (During the whole period the blinds of the north-facing windows were never in function).
- The Daylight Utilization Factors DUF_1, DUF_2 and DUF_3 for the 1st, 2nd and 3rd floor of the room. The Daylight Utilization Factor DUF is determined as the fraction of the working day during which the daylight replaces electric light.

The weather during the ten days was regarded as being "typical" for the time of the year. For the entire period the mean value of $E_{g,h}$ was $20.1 \cdot 10^3$ lux and the maximum value of $E_{g,h}$ was $83.6 \cdot 10^3$ lux. The time fraction for which the blinds were drawn was between 0.00 and 0.61.

The mean value of DUF for the three floors during the ten day period was $DUF_1=0.61$, $DUF_2=0.62$ and $DUF_3=0.85$. It is noticed that DUF_1 and DUF_2 are of the same size. This showed to be due to that the lighting on the 1st floor turned on/off at values of the interior illuminance that were rather low compared to the values at the 2nd and 3rd floor.

Generally speaking, there is a relatively good correlation between the daily values for $E_{mean\ g,h}$ and for the time fraction for which the blinds were drawn. On the contrary, no clear correlation exists between the daily En and DUF_1, DUF2, DUF_3. This is related to the fact, that DUF depends primarily on the available daylight in the morning and in the late afternoon, whereas $E_{mean\ g,h}$ is dominated by the conditions during the intervening hours.

<u>Set-points for blinds and the electric lighting</u>

Whether the blinds shall be drawn and whether the electric lighting shall be turned on, depend on the changes in the outdoor illumination level within the foregoing 2 - 20 minutes. Thus, there exists no exact "treshhold values" at which the motor for the blinds is activated and the electric light is turned on or off. In order to perform calculations as in chapter 3, it is necessary to define approximate "set-points". These are derived from the total amount of measured data.

Referring to $E_{g,h}$ the following approximate set-points were chosen. For the blinds: $30 \cdot 10^3$ lux. For the electric lighting on the 1st, 2nd and 3rd floor: $10 \cdot 10^3$ lux, $9 \cdot 10^3$ lux and $2 \cdot 10^3$ lux respectively. This corresponds to interior illuminance values (at the position of the measuring probes) of about 50 lux on the 1st floor and about 100 lux on the 2nd and 3rd floor.

Date	Cloud	Mean value and max. value of exterior global illuminance on horizontal $E_{mean\ g,h}$ klx	$E_{max\ g,h}$ klx	Fraction of time with the blinds in function	Daylight Utilization factor for the 1st, 2nd and 3rd floor DUF_1	DUF_2	DUF_3
Sept.14.	overcast	12.2	37.4	0.00	0.61	0.63	0.90
Sept.15.	lightly clouded	41.1	80.7	0.61	0.68	0.65	0.84
Sept.16.	overcast → cloudy	29.6	83.6	0.26	0.67	0.68	0.82
Sept.20.	cloudy → overcast	17.7	73.3	0.19	0.70	0.72	0.86
Sept.21.	cloudy	26.9	75.0	0.17	0.70	0.73	0.81
Sept.27.	cloudy	15.7	56.3	0.13	0.66	0.63	0.84
Sept.28.	overcast	6.1	17.8	0.00	0.35	0.35	0.87
Sept.30.	cloudy	19.8	63.4	0.08	0.63	0.65	0.91
Oct. 5.	misty	19.4	42.2	0.28	0.60	0.66	0.83
Oct. 6.	cloudy	11.2	43.6	0.03	0.51	0.52	0.82

Table 2.1. Main results from ten working days.

Illuminance of the electric lighting

The measurements showed that the illuminance of the electric lighting was about 70 lux on each of the three floors.

2.3.2. Typical lighting conditions during a one-day period

For one of the days (October 5th), figure 2.3. shows the variation of the outdoor global illuminance $E_{g,h}$ and the interior illuminance $E_{p,2}$ on the horizontal plane at the chosen position of the measuring probe on the 2nd floor.

It is noticed, that the electric light is on during the periods 5.10 a.m. - 7.30 a.m. and 4.30 p.m. - 6.10 p.m. The blinds are drawn between 10.20 a.m. and 1.45 p.m. giving a reduction of $E_{p,2}$ of about 50%.

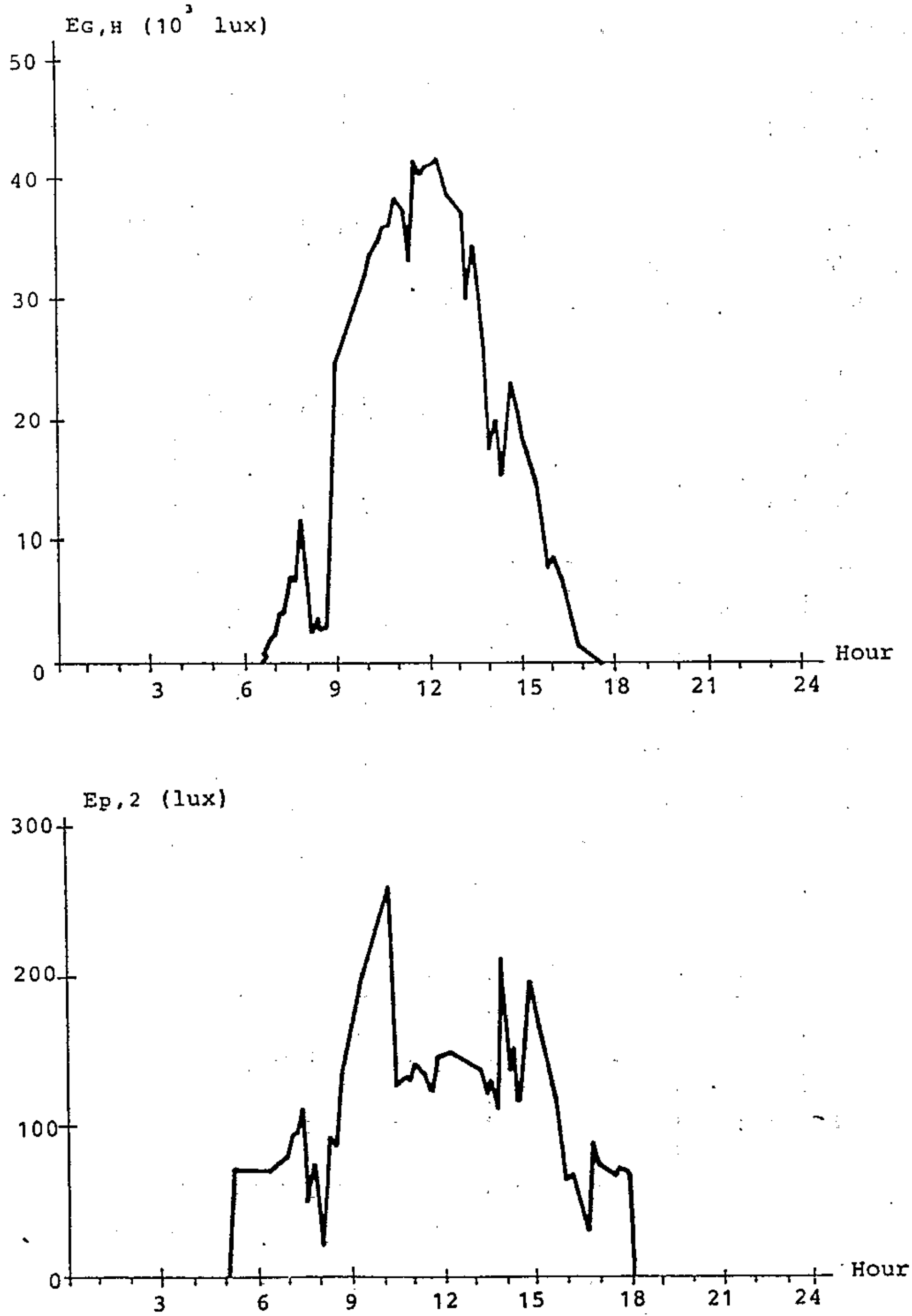


Fig. 2.3. The lighting conditions for the second floor on October 5th.

2.3.3. Distribution of the interior daylight

Detailed measurements of the Daylight Factor DF were carried out in order to illustrate the penetration of daylight from the rooflights to the corridors of the three storeys. The results were collected during two days with a completely overcast sky.

The results are shown on figure 2.4. - 2.5. At the middle of the open space under the rooflights the values of DF decreases from 24 at the top of the 3rd floor to 0.4 at the bottom of the 1st floor. When moving inwards from the fence to the walls of the corridors, there is a steep decline in DF, as the view factor to the rooflights (and with that the direct component of the daylight) decreases to zero.

The measured values for DF at the "standard" positions of the measuring probe on the three floors were: DF = 0.4 on the 1st floor, DF = 0.9 on the 2nd floor, and DF = 5.1 on the 3rd floor.

Considerable variations also occur along the vertical direction in the corridors. Measurements on the 2nd floor showed that DF was about twice as large at the flooring as at the standard position. Under the ceiling it was about half as large.

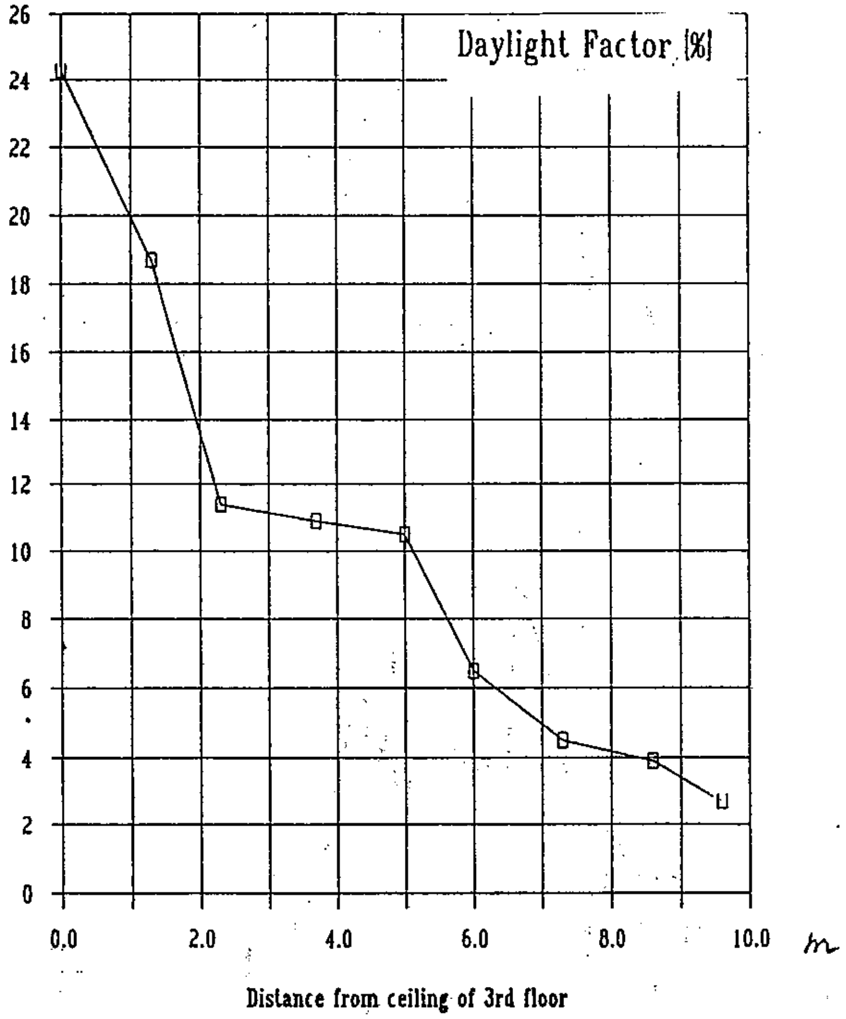


Fig. 2.4. Variation of the Daylight Factor in the vertical direction, according to measurements in the middle of the open space.

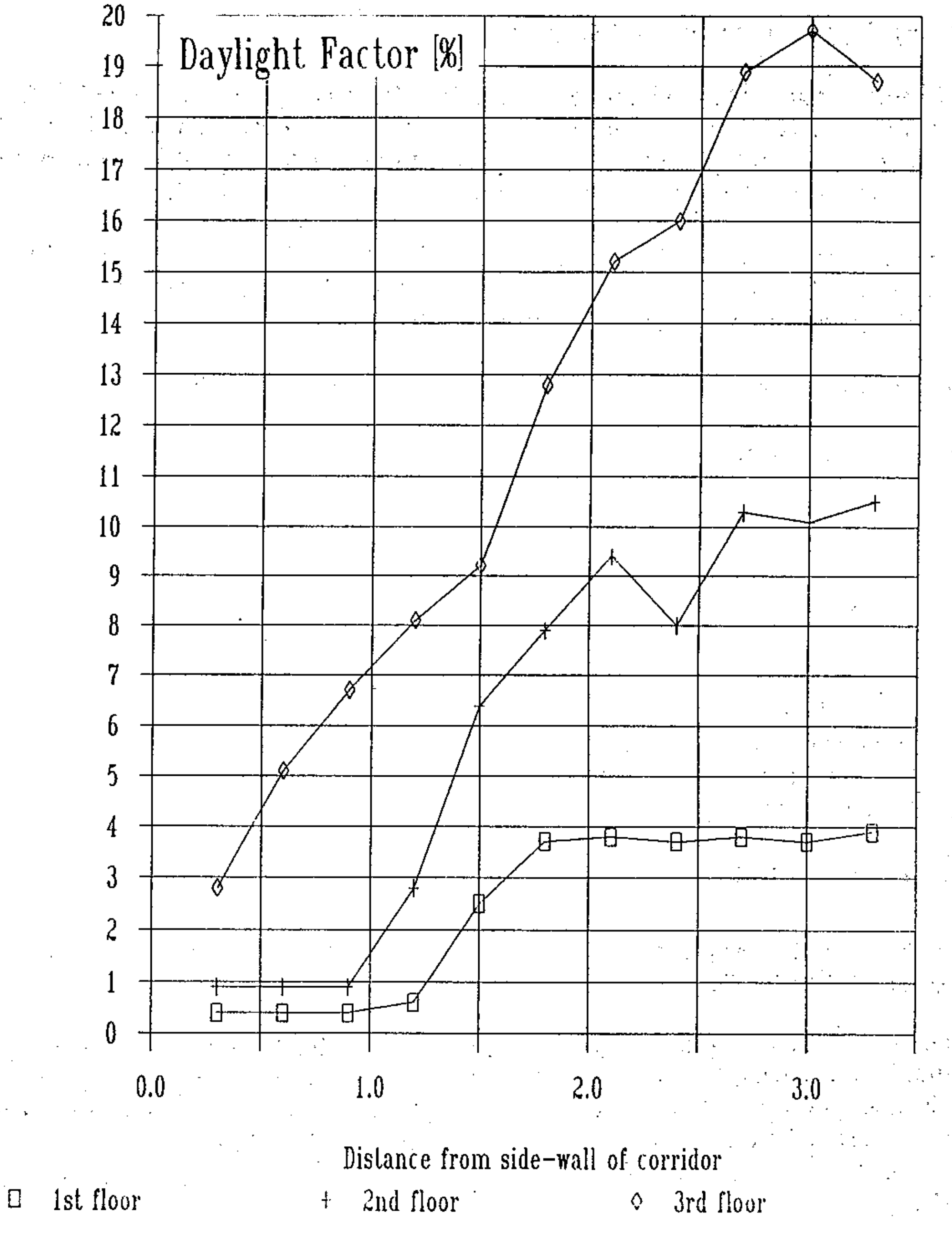


Fig. 2.5. Variation of the Daylight Factor in the horizontal direction, according to measurements 1 m above the flooring on the 1st, 2nd and 3rd floor.

2.3.4. Optical properties

Separate measurements were taken with the lux-meters in order to determine the characteristic optical properties relating to the room.

Transmittance of the glazing and the blinds

The transmittance of the window glazing τ_d for diffuse daylight was measured under conditions with radiation from a blue sky. The value $\tau_d = 0.78$ was obtained. It includes the effect of dirt on the glazing, which is supposed to be quite small at the time of the measurements, since the windows had been cleaned about two weeks before.

For two layers of normal float glass with the actual thickness, the value $\tau_d = 0.74$ is obtained from [2]. Since this value does not include the effect of dirt, the results indicate that the transmittance of the rooflight glazing is rather good.

The measurements led to a transmittance on 0.43 for the white cloth used for the blinds.

Surface reflectivities

The reflectivity of the different surfaces was measured under conditions with diffuse light from a grey sky, and the following results were obtained. The ceiling of the corridors: $\rho = 0.79$, the walls between the offices and the corridors:
$\rho = 0.71$, the vertical surface of the horizontal divisions between the stories: $\rho = 0.86$, the flooring: $\rho = 0.24$.

The "equivalent" reflectance of the open areas between the 1st and the 2nd storey and between the 2nd and the 3rd storey was also determined: The measurements gave that about 16% of the light, hitting the horizontal plane of the opening from above, was reflected back from the underlying surfaces.

2.4. Amenity issues

About ten of the people working in the offices were questioned concerning their opinion on the daylighting features of the building.

The general view was that the use of rooflights for daylighting is providing a very pleasant atmosphere in the arcade rooms. Nobody felt that there was ever any problems with glare. The interviews also reflected the fact that people are of course much more sensitive to the conditions in the offices than to those in the rooms for circulation. Thus several of the people had never noticed that the electric lighting of the circulation space was switched on/off automatically.

It should be mentioned that the automatic control of the blinds in front of the office windows was very unpopular among the occupants. It is possible to override the automatic control by manual operation, but the manually chosen position cannot be permanently fixed, i.e. after some time it will be changed according to the automatic control system. So on days with fast changing cloud cover, it is necessary to react time after time if one does not agree with the system, and this is felt to be very irritating.

3. CALCULATION OF PERFORMANCE

3.1. Modelling of lighting conditions

3.1.1. General

The performance of the "daylighting system" in the arcade rooms was investigated by means of the computer program DAYLITE. The structure and the capacity of the program are described in [3]. It is capable of making detailed calculations concerning the illuminance distribution in a given room at a given time of the year. Furthermore, hour-by-hour calculations can be made in order to determine the need for electric lighting during a "Standard Work Year".

The program runs on a PC. The editing of indata, execution of the calculations and presentation of the results are controlled by means of menu's, and so the program is rather easy to use.

The DAYLITE program is subjected to a general interest in connection with the work under the IEA task XI. Within this task an extension of the program (the socalled LITELINK) is being developed, which makes it possible to transfer the computed data for lighting energy consumption to a simulation program, that calculates the flows of thermal energy. This way an overall picture of the consumption of auxiliary energy for lighting, heating and cooling for a given building design in a given climate will be obtained.

3.1.2. The computer programme

Building configuration

The DAYLITE programme offers the possibility of describing several important features in relation to the design of apertures for daylight utilization. It is possible to describe ordinary windows in the facades, as well as configurations with windows in sawtooth roof forms, light wells and monitors. It is also possible to investigate the effect of using lightshelves and the shading effects from overhangs or sidefins.

On the other hand, it is a disadvantage that the shading effects from the surroundings (i.e. neighbouring buildings) cannot be taken into consideration by the programme. Movable shading devices (curtains or blinds) cannot be described either. The room geometry has to be a simple one with a rectangular floor plan. Interior obstructions (tables etc.) are not treated.

Several other programmes for lighting calculations exist, some of which are able to handle more complex room geometries. SUPERLITE [4] and BELYS [5] offer these possibilities, but they are not intended to be used at the PC-level, and they do not include the facility of determining the yearly consumption of energy for lighting.

Exterior illumination

The computations throughout DAYLITE is based on hour-by-hour values of the illuminance on a monthly standard day with an overcast sky and a monthly standard day with a blue sky. The illuminances due to diffuse light from the sky and due to direct sunlight on the plane of the aperture are determined according to the Robbins-Hunter prediction model [6]. The calculations are based on the geographic location, the assumed ground reflectance, and monthly Clearness Numbers. The Clearness Numbers (based on solar radiation data from the Danish Test Reference Year [7]) were prepared by the authors of the programme.

At the calculations of the monthly need for electric lighting, a monthly weighted average day is used. Each hour consists of certain time fractions with the conditions of the day with the grey sky and the conditions of the day with a clear sky. The weighting of the time fractions is carried out by the use of a sunlight probability model [6]. (The sky is assumed to be clear if the global solar irradiance on horizontal exceeds 200 W/m^2).

An impression of the available daylight for each month is obtained from table 3.1. The table shows the mean value of the calculated global illuminance on horizontal $E_{mean\ g,h}$ during the light hours of the day. The table also shows the daily number of hours with daylight and the percentage of the working day (from 5.15 a.m. to 18.15 p.m.) during which daylight is available. It is noticed, that the mean value for $E_{mean\ g,h}$ of $20.1 \cdot 10^3$lux that was obtained during the period of the measurements is very close to the values that are stated for September and October.

Month	Mean value of outdoor global illuminance on horizontal $E_{mean\ g,h}$ klx	Daily number of hours with daylight	Percentage of working day with daylight
Jan.	11	7	54
Feb.	17	9½	73
Mar.	26	12	92
Apr.	33	14	100
May	29	16½	100
Jun.	35	17	100
Jul.	31	16	100
Aug.	31	14	100
Sep.	23	12	92
Oct.	18	9½	73
Nov.	11	7	54
Dec.	7	6½	50

Table 3.1. Characteristics concerning the available exterior daylight.

The monthly number of lux-hours, that is obtained from the data calculated by DAYLITE, was compared to the number that can be obtained by simply dividing the monthly global insolation on horizontal (according to [7]) by 110 lm/W. This is a representative mean value for the luminous efficacy of daylight in the Danish climate according to [8]. The deviations showed to be quite large for the months January, February and March (up to 40%), which indicates that the daylight levels calculated by the programme are somewhat too optimistic during these months.

Interior illuminance from daylight

The interior illuminance from daylight is calculated in a network of up to 49 station points, distributed in the horizontal directions of the space. The distance above the floor (the "work plane height") is stated by the user. The illuminance is calculated by means of the Flux Transfer Method [6], and the internally reflected illuminance can be determined as the average value or (at the expense of computation time) by using a point-specific method.

The interior illuminance calculations may be followed by a comfort analysis in order to investigate the glare index and the contrast ratio.

Electric lighting

Upon the computation of the interior daylight illuminances, hourly electric lighting calculations are performed. The calculations are related to the desired minimum lighting level and the chosen electric lighting control strategy. It is possible to choose an automatic on/off switching, an automated step-switching (3- 4- or 5-step) or an automated continuous dimming.

The programme calculates the monthly fraction of the required lighting (in lux-hours) that is met by daylight. For an on/off control system this Daylighting Fraction corresponds to the Daylight Utilization Factor DUF, that was used for describing the results of the measurements in section 2.3.1.

Finally, a lighting power budget can be prepared. This includes a survey of the monthly Unit Power Density, i.e. the average power that is needed for lighting per m^2 of the floor area.

3.1.3. Model of the arcade room

Since it is not possible to describe the overall geometry of the arcade room in the DAYLITE programme, a model for each of the three floors was set up. In each case, a "Sawtooth" description was used for the roof.

For the 2nd and the 3rd floor, the opening to the underlying storeys was regarded as being part of a uniform floor space. (The reflectance of the floor was the area-weighted mean value of the reflectance of the real floor and the "equivalent" reflectance of the opening). For the 1st and the 2nd floor, the space between the ceiling of the corridor and the roof-light is modelled by specifying an equivalently large thickness for the roof structure. The illuminance on the 1st and the 2nd floor was reduced by a constant correction factor in order to account for the losses due to distribution of light to the corridors of the above-lying storeys. These factors were simply derived as the appropriate adjustments that would give a reasonable agreement between the measured and calculated distribution of the Daylight Factor. The measured and the (corrected) calculated values are compared in table 3.2.

		Distance from station point to the side wall of the corridor			
		0.6 m	1.5 m	2.4 m	3.3 m
3rd floor	measured calculated	5.1 5.1	9.2 13.0	16.0 17.4	18.7 19.4
2nd floor	measured calculated	0.9 1.8	6.4 1.8	8.0 8.9	10.5 8.2
1st floor	measured calculated	0.4 0.6	2.5 0.6	3.7 3.3	3.9 3.1

Table 3.2. Measured and calculated Daylight Factors on the three floors (1 meter above the floor of the corridors).

It was not possible to model the movable blinds, but since they are only drawn in case of high values of the exterior illuminance, they will not significantly influence the electric lighting consumption.

The set-point for the on/off control of the electric light was fixed at 100 lux for the station point 0.6 m from the side wall of the corridor. According to company specifications the luminous efficacy of the lamps is 50 lm/W. The total power consumption of one lamp is 21 W, corresponding to a power consumption of 7.8 W per m^2 of the floor area of the corridors.

The DAYLITE programme does not provide the possibility of making a detailed validation of the model by using the measured data for hourly external illuminance. However, an indication of the validity of the model can be obtained by comparing the mean values of DUF as measured and as computed for September, as shown in the preceeding section.

3.2. Energy savings

3.2.1. Yearly performance of daylighting

The monthly values of DUF, that was calculated for the three floors, is shown in table 3.3. The mean value for all floors of the arcade room is shown in figure 3.1. The variations between winter and summer are 0.28-0.74, 0.28-1.00 and 0.43-1.00 for the 1st, 2nd and 3rd floor respectively. The yearly mean values are 0.52, 0.71 and 0.80 for the three floors and 0.68 for the room in general. According to the monthly number of daylight hours, the maximum possible yearly value of DUF is 0.83.

It is noticed that the value of DUF for September (= 0.72) is rather close to the mean value for the period of the measurements (= 0.70), indicating that the calculations are fairly reasonable.

	DUF_1	DUF_2	DUF_3
Jan.	0.31	0.31	0.54
Feb.	0.39	0.53	0.69
Mar.	0.58	0.77	0.85
Apr.	0.66	0.93	1.00
May	0.61	1.00	1.00
Jun.	0.74	1.00	1.00
Jul.	0.63	1.00	1.00
Aug.	0.60	0.94	1.00
Sep.	0.51	0.79	0.85
Oct.	0.49	0.60	0.69
Nov.	0.38	0.38	0.54
Dec.	0.28	0.28	0.43
Year	0.52	0.71	0.80

Table 3.3. Calculated values for the Daylight Utilization Factors DUF_1, DUF_2 and DUF_3 for the 1st, 2nd and 3rd floor of the arcade room.

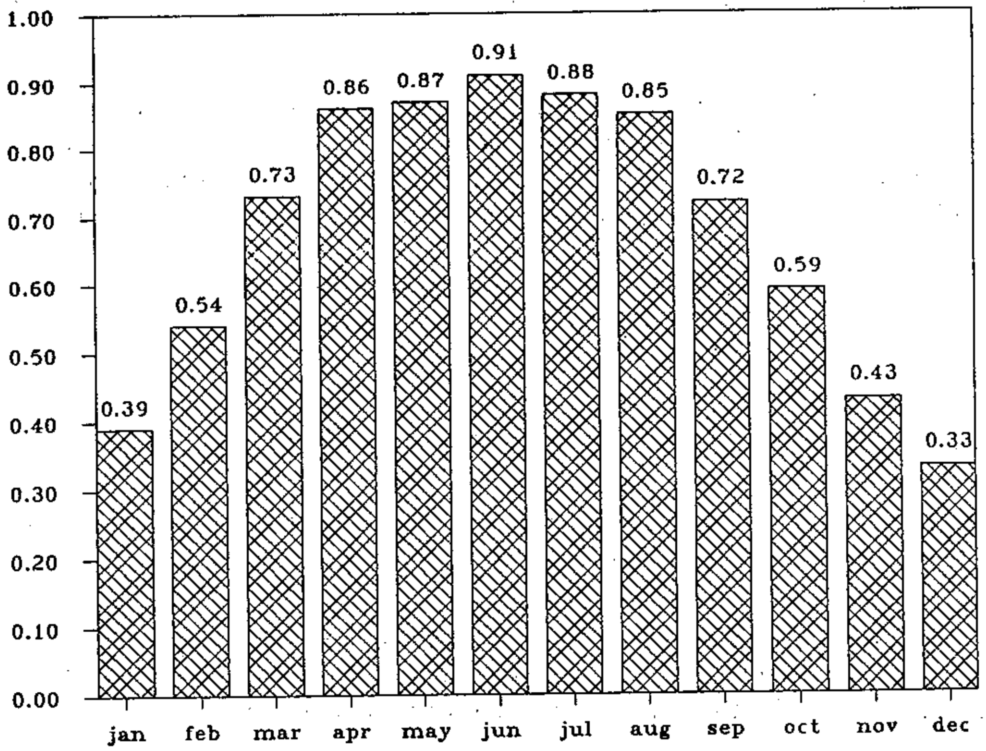


Fig. 3.1. Monthly mean values for the Daylight Utilization Factor DUF of the 3-storeyed arcade room.

The values for DUF express the relative savings of the electrical energy that would be needed for lighting, if there was no contribution from daylight. In the following is used the yearly energy savings ΔQ per m^2 of the circulation area. In case of the on/off control system ΔQ is found from

$$\Delta Q = \text{DUF} \cdot 26 \text{ kWh/m}^2 \text{ year}$$

where the constant is obtained from the product of the electric lighting power density (7.8 W/m^2) and the total number of hours with lighting (3380 hours).

Thus, in the present case the yearly energy savings will be 14 kWh/m^2, 19 kWh/m^2 and 21 kWh/m^2, corresponding to a mean value of 18 kWh/m^2. Using the total area of the corridors on the three floors of the office block (excluding the central floor area of the 1st floor) leads to total energy savings of $37 \cdot 10^3$ kWh/year. However, as mentioned in section 1.2. a considerable part of the area is not included by the automatic control system. Due to this reason, the real savings will only be about $26 \cdot 10^3$ kWh/year.

The savings are proportional to the power consumption of the lamps. Thus, if it for instance was chosen to use incandescent lamps with an efficacy of 13 lm/W, the savings would be about four times as large.

3.2.2. Parametric studies

The influence of several important parameters was investigated by means of the computed model. These were:

- The use of automated continuous dimming of the electric light.
- The influence of the desired minimum lighting level.
- The size of the window area.
- The length of the Standard Work Day.

Continuous dimming

Figure 3.2. shows the energy savings that can be obtained by continuous dimming of the electric light rding to the available daylight. The lowest value of the input power to the ballast of the lamp is assumed to be 15% of the normal level. The savings can be increased by 25% on the 1st floor, 9% on the 2nd floor and 1% on the 3rd floor, i.e. there is a significant improvement on the two lower floors where the Daylight Factor is rather low.

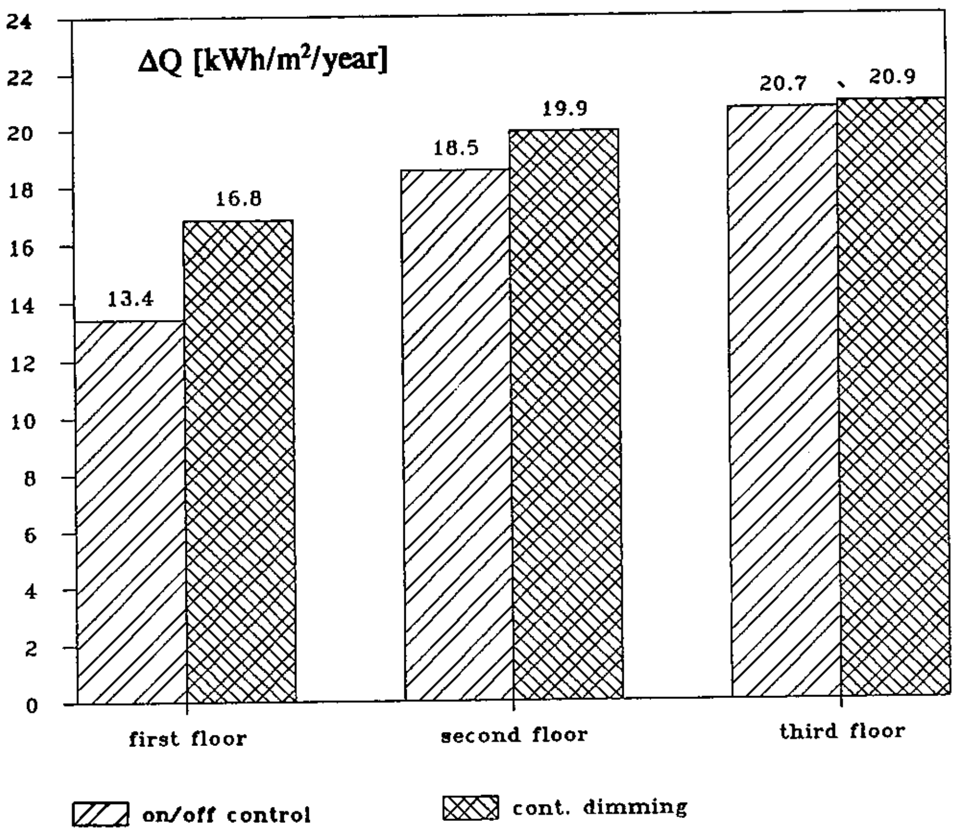


Fig. 3.2. The energy savings by using automated continuous dimming of the electric light compared with the saving by using an on/off control.

Minimum lighting level

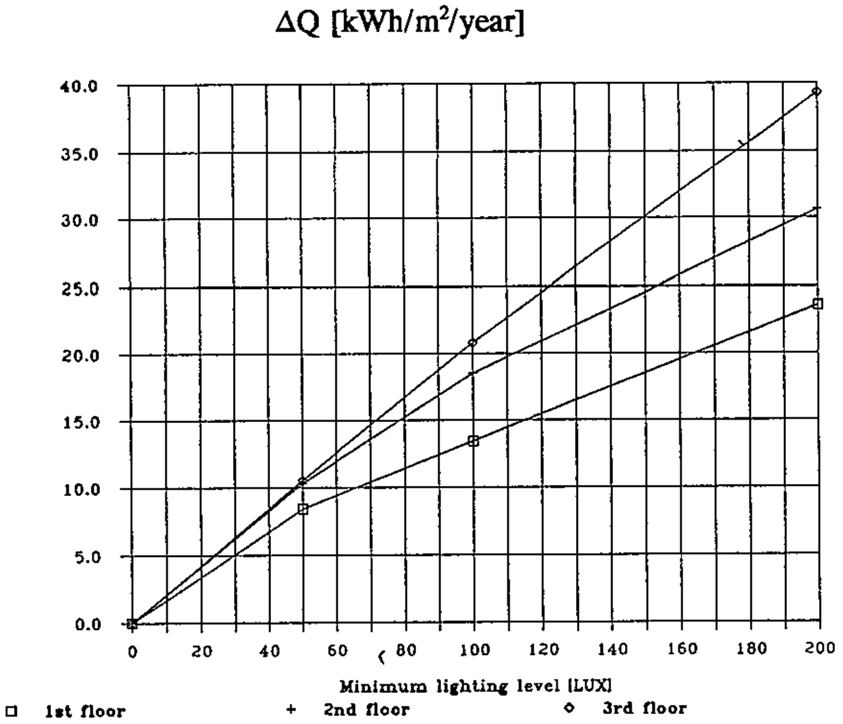


Fig. 3.3. The influence of the desired minimum lighting level on the energy savings.

The influence of this parameter is shown on figure 3.3. It is assumed, that the luminous efficacy is the same as in the reference case. It is noticed, that there is an almost linear connection between ΔQ and the required lighting level.

Size of window area

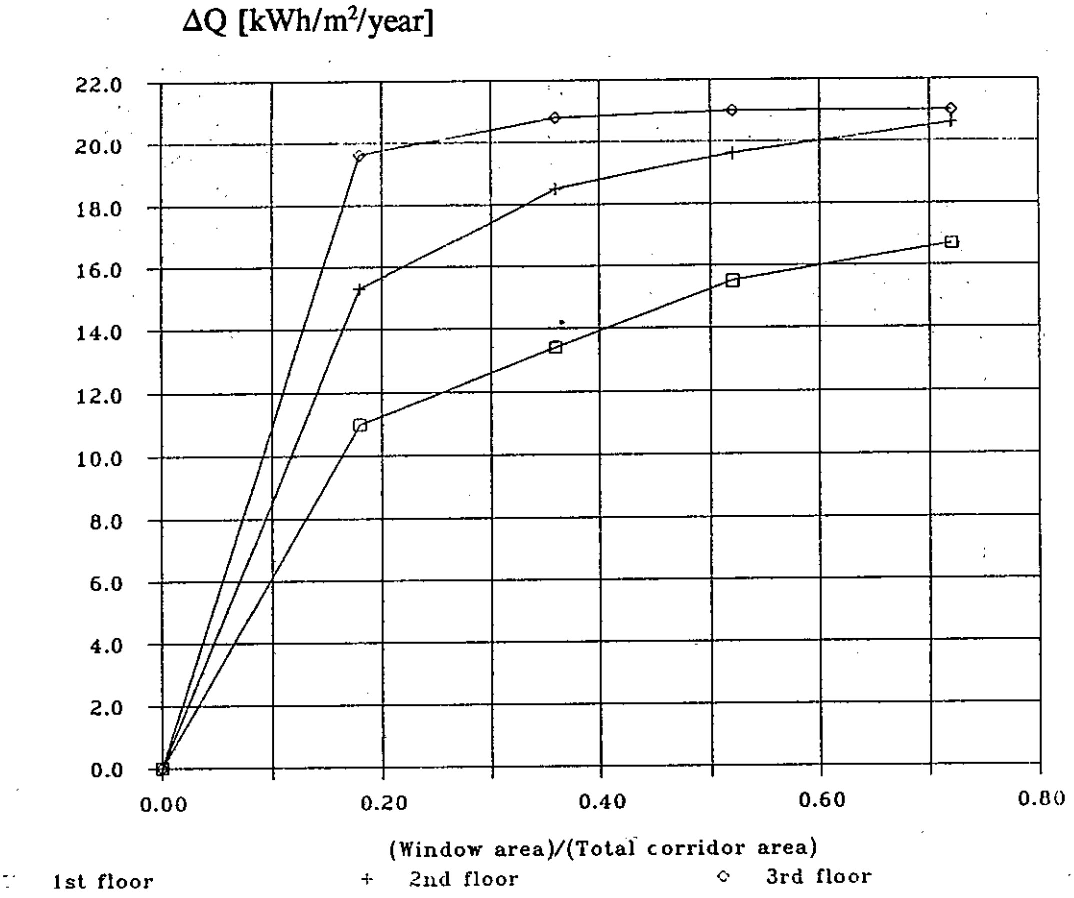


Fig. 3.4. Dependence of the energy savings on the ratio between the window area and the total floor area of the corridors. For the actual building this ratio was 0.36.

The importance of the size of the window area is illustrated on figure 3.4. The energy savings are hown as a function of the ratio of the window area to the total floor area of the corridors on the three floors. For ratios larger than about 0.20, an increased ratio will only give a modest increase of ΔQ on the 3rd floor, whereas there will be some increase on the 1st floor. If the window area is doubled, the total energy savings on all floors will be increased by 6%.

Length of Standard Work Day

The length of the Standard Work Day of 13 hours used in the actual building is somewhat longer than what is used in normal daylight calculations. Thus, a length of 10 hours from 7.30 a.m. to 17.30 p.m. will be more typical.

The significance of choosing these values was investigated, and the results are shown in figure 3.5. As expected the values of DUF will increase somewhat. That way, the relative decrease in ΔQ will be limited to between 5% and 13% for the three floors.

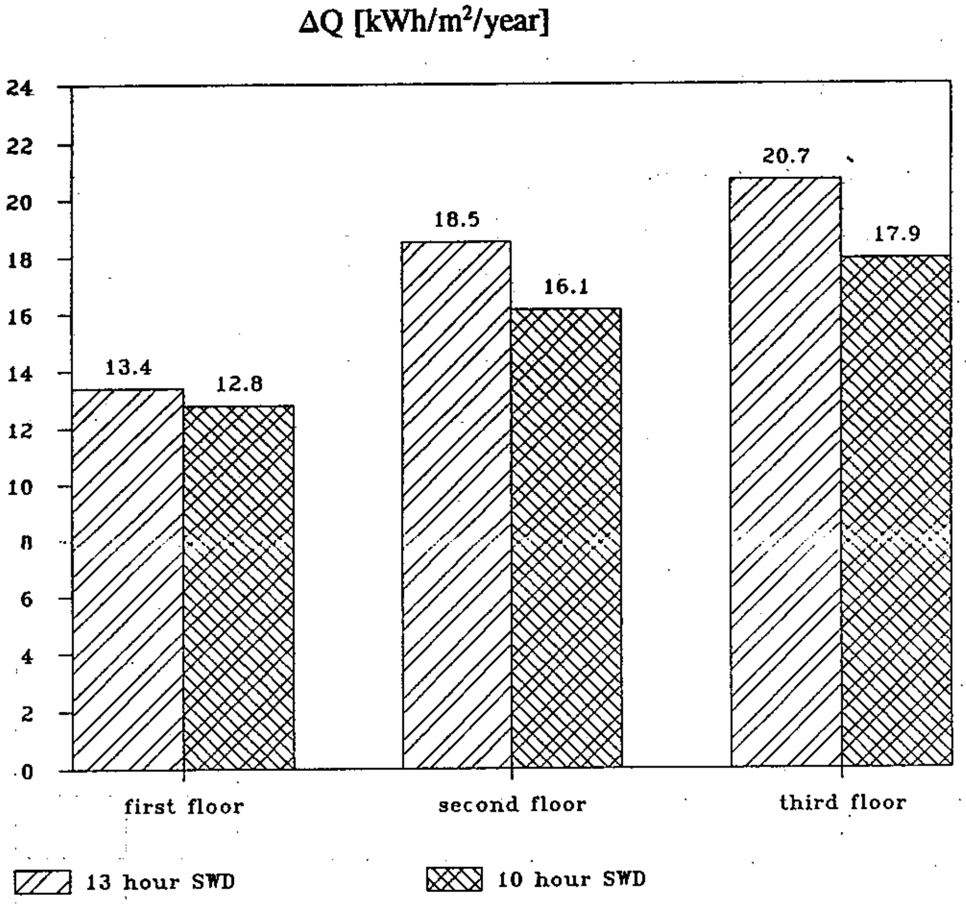


Fig. 3.5. Comparison of energy savings for Standard Work Days of 13 hours and 10 hours.

3.3. Economic considerations

With an electricity price of 0.77 Dcrs (Danish crowns) per kWh, the energy savings by using the rooflights and the automatic electric lighting control will amount to about 14 kr/year per m² of the corridors, or 28,000 kr/year for the whole building. Taking the area of the rooflights as a reference, this corresponds to 37 Dcrs/year per m² of the windows.

In order to evaluate the economic benefits by using the rooflights for daylighting, the value of the energy savings should be compared with the prize of the additional space between the corridors. This includes the extra expenses of the glazed roof, flooring, ground slab, etc. Also the costs of the blinds, and the electric lighting control system should be considered. It is evident that these expenses will be very high compared to the energy savings, and by that the total arrangement for daylighting will not be very cost-effective. Still, the successful use of daylight holds very large benefits seen from the point of view that it influences the well-being of the occupants, and this quality is of course very hard to evaluate.

4. CONCLUSION

The daylighting of the circulation area in the BRF Headquarters has proven to be successful. By the use of rooflights in combination with an automatic on/off control of the electric lighting, significant energy savings are obtained. At the same time, the daylight provides a pleasant atmosphere in the room.

The measurements during about three weeks gave a detailed understanding of the lighting conditions, and the results provided important informations to be used at the preparation and the assessment of the computer model.

Regarding the lighting control system, it showed to be a good idea to use only one exterior photo cell and "translating" the signal from this into lighting levels for all three floors by the computer of the energy management system. - However, the "set-point" of the electric lighting on the 1st floor was somewhat too low compared to the other floors, but this can be adjusted by a simple change in the programming.

According to the computer simulations, the yearly energy savings will be 52% on the 1st floor, 71% on the 2nd floor and 80% on the 3rd floor. Per m^2 of the corridor area this corresponds to 13 kWh/year, 19 kWh/year and 21 kWh/year.

The parametric studies showed that there are large differences from floor to floor in the sensitivity to the parameter changes. Thus, by the use of continuous dimming the savings will increase by 25% on the 1st floor, whereas on the 3rd floor they will only increase by 1%. I.e, the effect of the changes on the "darker" areas is much more pronounced than on the "lighter" areas. The size of the window area showed to be appropriate seen from the point of view of saving electric lighting. By doubling the area, the total savings for all of the floors will not be increased by more than 6%.

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Advanced Case Study

Technologiezentrum, Stuttgart

Preface

A description of the Technologiezentrum Stuttgart is given in the Base Case [1].

The building is a two-storey linear atrium with office rooms connected to the atrium and additional north and south facing office spaces directly connected to the environment. The rooflight in the linear atrium is east/west oriented. Apart from that, no special daylighting features are included.

Measurements concerning the manual on/off lighting control and the use of shading devices were carried out by the Fraunhofer-Institute of Building Physics, Stuttgart, [2] in an office with one zone connected to the atrium and another to the south facing environment. The measurements were conducted to determine the saving potential of lighting control equipment and the reduction of daylighting potential caused by the use of shading devices.

Introduction

A view of the atrium of the Technologiezentrum is shown in fig. 1. It was intended that the atrium should supply the adjacent office rooms with daylight and fresh air. The rooms have double-glazed windows oriented towards the atrium.

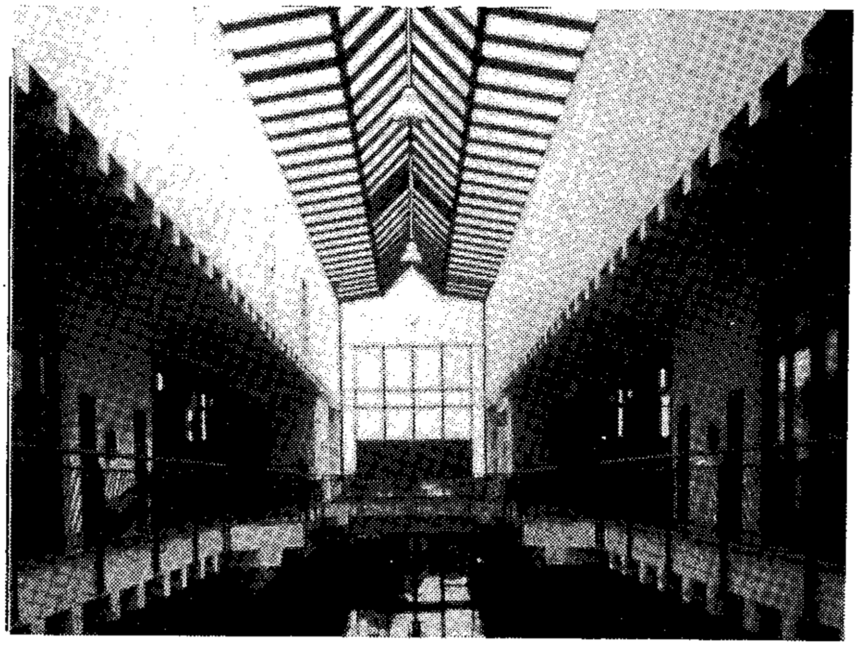

Fig. 1: View of the atrium of the Technologiezentrum Stuttgart, with the adjacent office rooms, overhangs and lightwells.

The atrium itself is glazed with 7 mm wired clear glass. The rooflight is east/west oriented and has a width of 5.5 m. Painted lightwells, 4 m high, should reflect direct sunlight into the space. Overhangs, 2 m wide, are placed above the windows of the adjacent spaces. A desired service illuminance of 500 resp. 150 lux was fixed for all the office rooms and the secondary room.

In the office rooms connected to the environment, adjustable blinds operate as shading devices. In the rooms connected to the atrium, such devices are not necessary. The shadings are adjusted manually by the occupants.

Measurements

The measurement equipment was installed in the occupied office presented in fig. 2. In zones I and II, a chemical laboratory was installed, while zone IV was used for ordinary office work. Zone III, which did not have a representative character, served as an entrance.

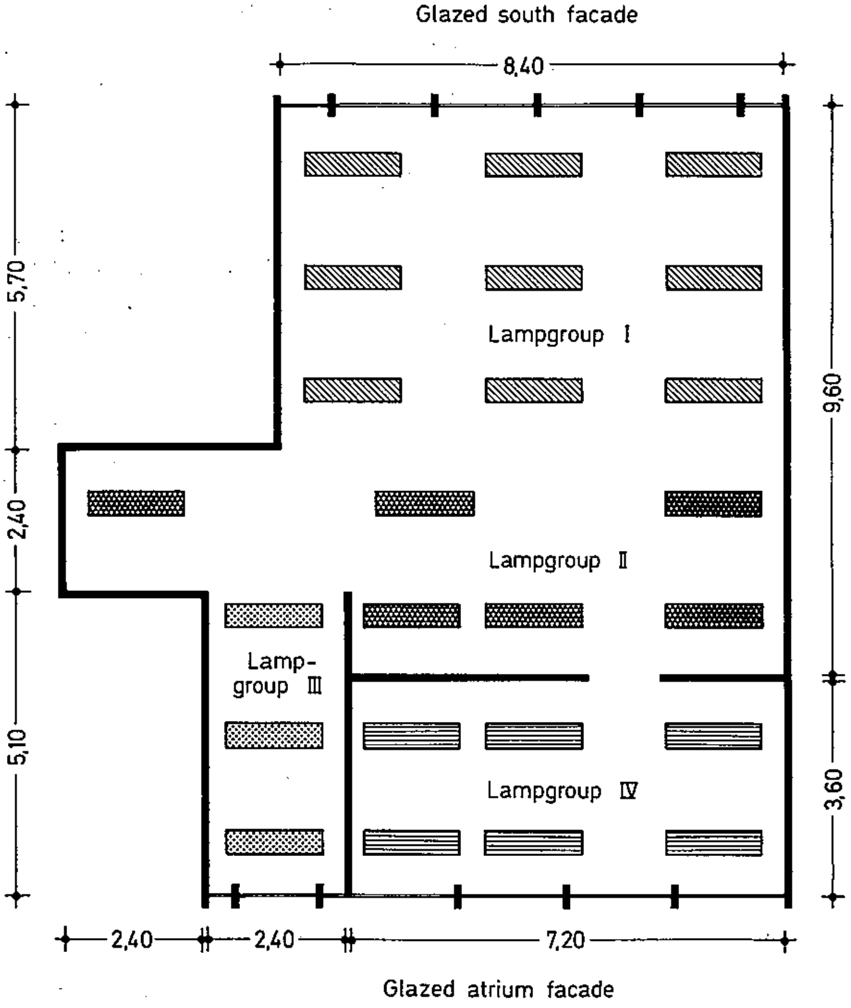

Fig. 2: Floorplan of monitored office room in the Technologiezentrum Stuttgart. Manual lamp control and use of shading devices were monitored during 10 weeks.

The following measurements were monitored continuously (every 15 minutes) during 10 weeks in autumn 1989:

- monitoring of on/off switched lamps
- monitoring of all lampcircuits
- positon of shading devices
  (venetian blinds) on the south facade

Measurements were conducted to gauge the behaviour of the office personnel regarding:

- use of artificial lighting
- use of shading devices

Results

USE OF ARTIFICIAL LIGHTING

The results concerning the use of artificial lighting in the monitored office are exemplarily shown in fig. 3 for a specified week in October 1989. During that week, the weather was sunny and warm. The figure illustrates the manual switch on/off characteristic of the 4 different lampcircuits. From this figure more or less regular patterns can be recognised.

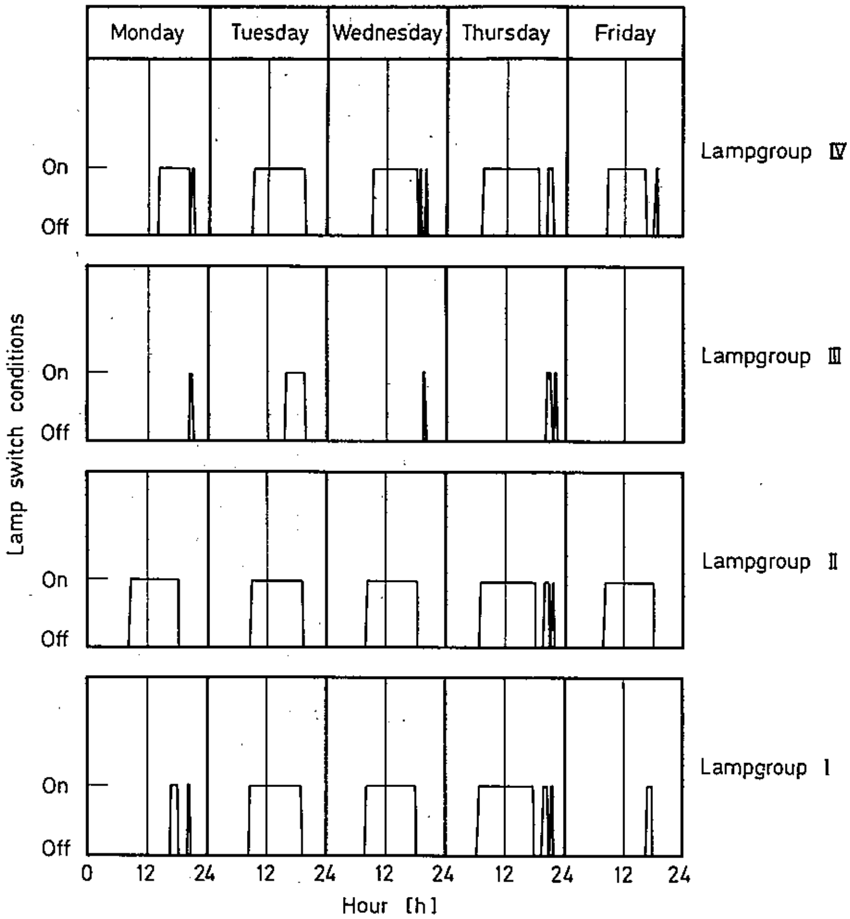

Fig. 3: Status of the artificial lighting in the monitored office of the Technologiezentrum Stuttgart in the week of 23 to 27 October 1989. Four different zones are presented.

Interesting are some regular peaks in all zones which occur during the late afternoon. These peaks correspond to the time when the cleaning service is in the office. If the lights are out when the cleaner arrives, he switches on all circuits; otherwise the whole lighting is turned off when the cleaner finishes his job.

In lampgroup I, which is closest to the south facing window in the laboratory, lamps are burning less often compared to the zone of lampgroup II. In lampgroup II, the lamps remain switched on most of the day. This indicates that it may occur that zone I is sufficiently daylit when people start working, so that they do not need additional light. There is no indication that a specific quantity of light induces people to turn off the artificial lighting when enough daylight is available. In zone III, which is the entrance, lighting is used very seldom, which does not indicate that it is sufficiently daylit but that it is an entrance with no representative character. In zone IV, which is the ordinary office connected to the atrium, light was burning nearly all day during that week. This room seems not to be sufficiently daylit by the atrium.

Figure 4 shows the hours when lights are switched on for the four different zones (for the above mentioned week). Besides, the specific electric power in the different zones is also given. This electric power represents internal heat gains for the office.

		Running hours per week [h]	Specific weekly internal gains by lighting [Wh/m²w]
Daylit office	Near to window	36,75	510
	Far from window	53,50	660
Entrance		6,50	110
Office connected to atrium		47,50	840

Fig. 4: The table shows the weekly switch-on hours of the artificial lighting and the resulting internal heat gains in the Technologiezentrum Stuttgart in the week from 23 to 27 October. The values of the four different zones shown in fig. 2 are presented. The mandatory weekly flexible working time was 39 hours.

The percentage of switched on lamps in the 4 different zones is shown in fig. 5 for the entire monitoring period. From the figure below it can be seen that in zone II, which is the inner zone of the laboratory office, the lamps were switched on during 80 to 85 % of all hours during the monitoring period (weekends excluded).

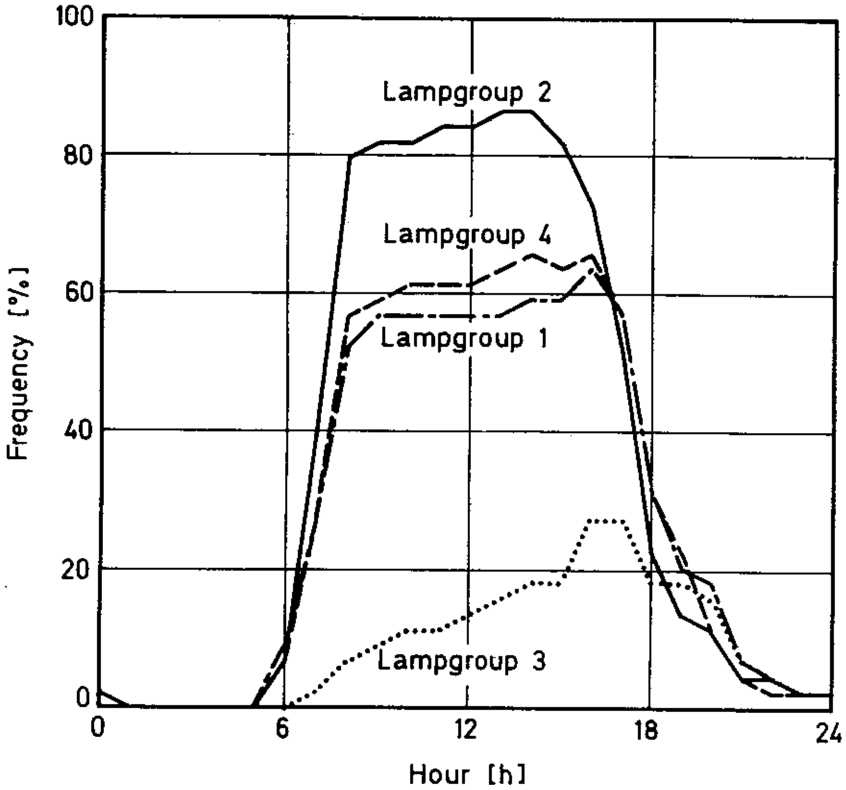

Fig. 5: Percentage of frequency of switched-on lamps in the 4 different zones for the whole monitoring period (weekends excluded).

Zone I (near to south facing window) and zone IV (connected to atrium) show surprisingly good agreement. In fact, in zone IV the light is switched on more frequently compared to zone I. This can be explained by the fact that the room connected to the atrium gains less daylight than the room connected to the environment. An interesting point is the tendency for the lights to be switched on only in all zones during the day until the afternoon. This leads to higher internal heat gains due to lighting in the afternoon (when overheating can also occur!).

In figs. 6 and 7, this tendency is exemplarily illustrated in detail for zone IV (connected to the atrium).

Clearly, from the figures below, it can be deduced that artificial light is mainly switched on twice during the day, namely in the morning and in the afternoon, whereas it is only in the afternoon that the light is turned off. This means that in the monitored office, users do not care about wasted lighting energy; otherwise they would turn off the light - at least during lunchtime and whenever their requirements are satisfied by the available quantity of daylight alone. On arriving at the office, the occupants consider whether they need additional light at this time. During the day, more and more artificial light is being turned on, particularly in the afternoon when daylight drops and the occupants recognise that daylight gets poor, unless they have already turned on the light.

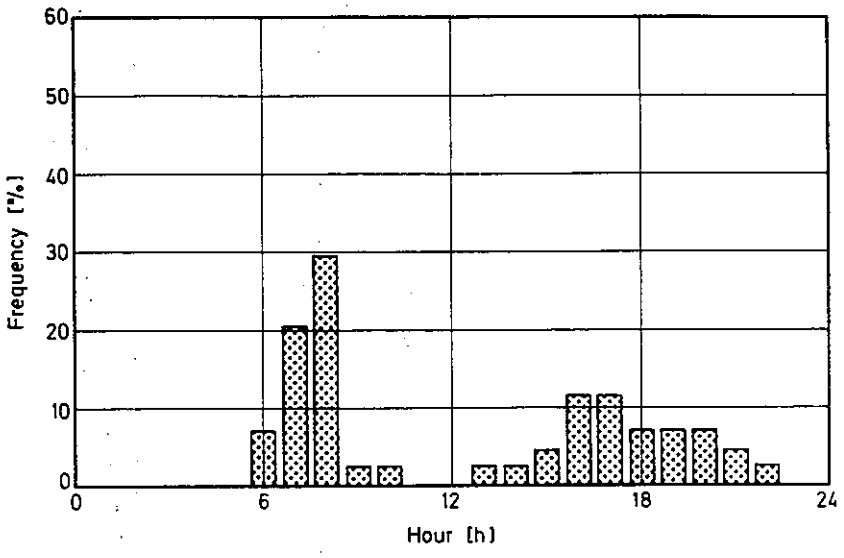

Fig. 6: Hourly switch-on frequency of lampgroup IV in the Technologiezentrum Stuttgart for the whole monitoring period in autumn 1989.

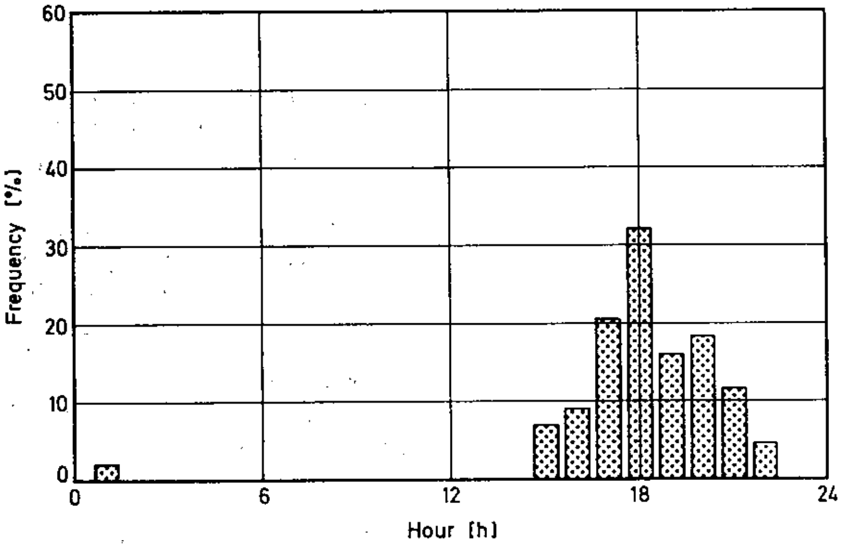

Fig. 7: Hourly switch-off frequency of lampgroup IV in the Technologiezentrum Stuttgart for the whole monitoring period in autumn 1989.

USE OF SHADING DEVICES

All windows at the south facade are provided with aluminium venetian blinds with adjustable tilts as shading devices.

In fig. 8 the use of the shading devices of the windows at the south facade is shown for window I as an example. The figure shows the mean length of the venetian blind during the monitoring phase. The total window height was 1.5 m. The figure shows that in this office room on an average nearly 2/3 of

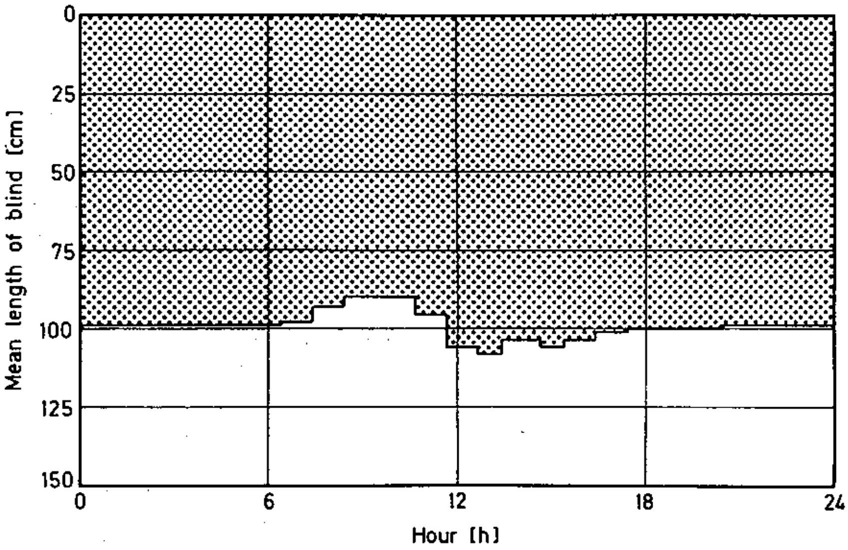

Fig. 8: Mean length of the venetian blind before window I at the south facade of the monitored office as observed for the whole monitoring phase.

the window was shaded by the venetian blind. Only at the bottom of the window about 50 cm of the glass was not shaded to have visual contact with the environment. In the morning, the blind is generally pulled up, whereas in the afternoon it is pulled down. When the occupants leave the office the length of the blind remains as it is adjusted in the afternoon. The frequency of manual blind moving is shown in fig. 9.

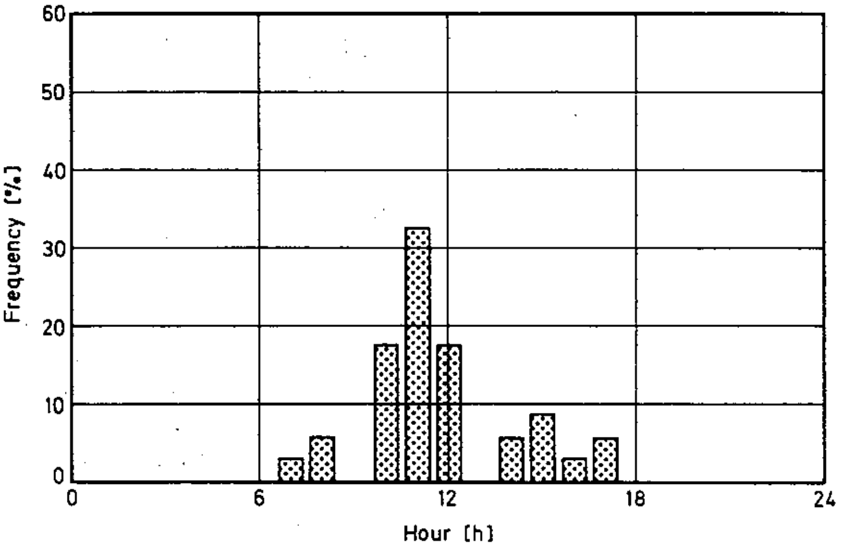

Fig. 9: Mean hourly frequency of manual blind moving before window I at the south facade of the monitored office during the whole monitoring phase.

This figure shows the mean hourly frequency of blind moving during the entire monitoring period, window I serving as example. In this figure, 3 main periods of blind moving are visible. It is of interest to note that in each period, the occupants might have different motivations for blind moving:

a) in the morning (even in summer and autumn) the occupants arrive at the office, open the window for a while to let in fresh air and pull up the blind a little bit.

b) at noon (especially in autumn and winter for low sun noon angles) the occupants are exposed to glare problems and pull the blind down.

c) in the afternoon, when overheating may occur (in summer and autumn), the blind is pulled down. When making this decision, the occupants do not consider internal heat gains due to artificial lighting which is often switched on in parallel.

A use of the venetian blinds as daylighting devices by manual adjustment of the tilts of the single blinds has not been observed.

Conclusion

Manual lamp control and use of shading devices in office rooms were investigated over a period of 10 weeks in late summer and autumn 1989 in the Technologiezentrum Stuttgart.

From the measurements it can be concluded that artificial lighting is switched on in office rooms for the major part of the working day. In zones which are daylit either directly or through the connected atrium, the light was switched on during app. 60 % of all monitored working hours, while in zones with poor daylighting the light was burning during app. 85 % of all working hours.

During the day, more and more light is switched on mainly in two periods per day: in the morning, when the work starts, and in the afternoon.

The shading devices were used for different purposes during the day, mainly to avoid glare at noon and/or avoid overheating in the afternoon (while artificial light was on!).

From the above, the general conclusion can be drawn that frequently manual light and shading device control do not lead to adequate, energy-efficient use of lighting and shading systems. The potential for measures to decrease the energy used for lighting and cooling in buildings is worth a thorough examination in the future.

This investigation was funded by the German Ministry of Research and Technology in the framework of the German participation in the IEA-TASK XI project.

References:

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Advanced Case Study

ZÜBLIN, Stuttgart

Preface

A description of the Züblin Building, Stuttgart, is given in the Base Case Study [1].

The building is a 33 m high, seven-storey linear atrium with office rooms connected to the atrium and additional east and west facing office spaces directly connected to the environment. The linear atrium is north/south oriented. Apart from that, no special daylighting features are included.

Measurements concerning the manual on/off lighting control were carried out by the Fraunhofer-Institute of Building Physics, Stuttgart [2], in an office with one zone connected to the atrium. The measurements were conducted to determine the saving potential of lighting control equipment.

Introduction

An outside view of the atrium is shown in fig. 1. It was intended that the atrium should supply the adjacent office rooms with daylight and fresh air. The rooms have double-glazed windows oriented towards the atrium.

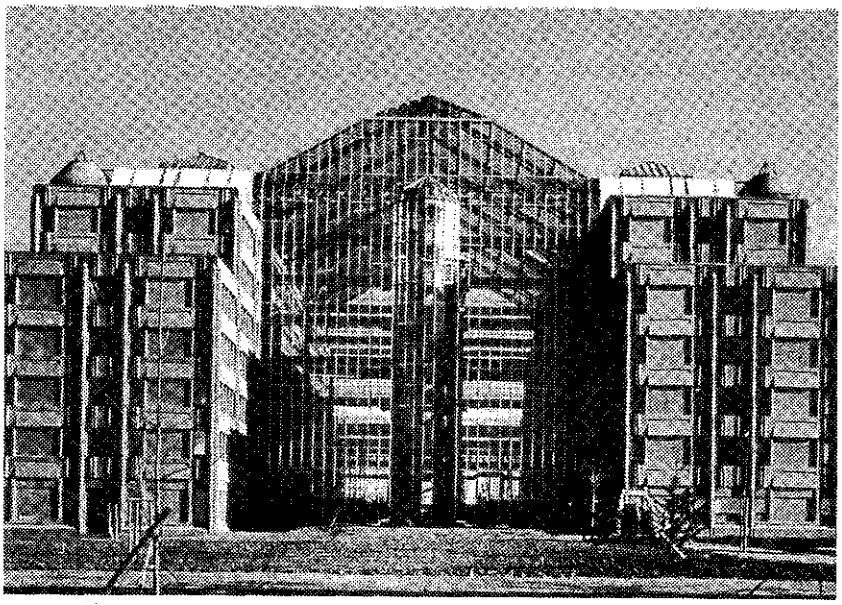


Fig. 1: Exterior view of the atrium.

The atrium itself is glazed with puttyless single safety glazing. The atrium is north/south oriented and has a width of 24.50 m. A desired service illuminance of 500 lux was fixed for all the office rooms.

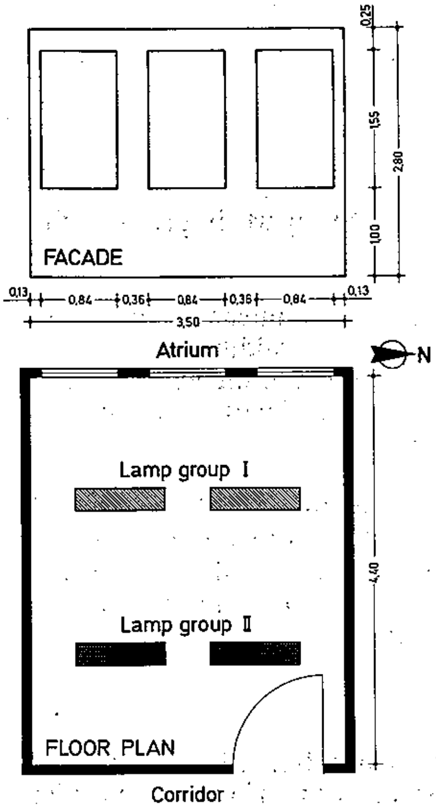


Fig. 2:
Floor plan and facade view of monitored office room in the Züblin building, Stuttgart.

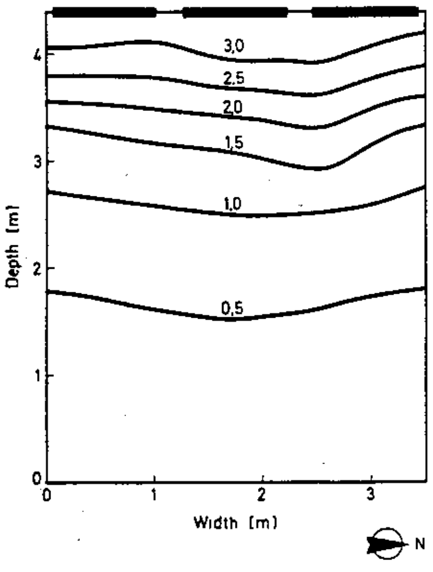


Fig. 3:
Daylight factor distribution in the monitored office.

Measurements

The measurement equipment was installed in the occupied office presented in fig. 2. The office was placed on the third floor of the south-eastern part of the building. Thus, the windows of the monitored office were facing west. Zones I and II were used for ordinary office work.

The following measurements were monitored continuously (every 15 minutes) during 1990:

- monitoring of on/off switched lamps
- monitoring of all lamp circuits

Measurements were conducted to gauge the behaviour of the office personnel regarding the use of artificial lighting.

Also, the daylight factor was measured under overcast sky conditions.

Results

Daylight factor

The daylight factor distribution of the monitored office was measured once under overcast sky conditions. The measurements were carried out on a horizontal plane, 0.85 m above the floor. The resulting daylight factor distribution is shown in fig. 3.

The minimum daylight factor in the room was 0.2 (at the corridor wall), the maximum value was 3.3 (next to the window). The asymmetric distribution can be explained by the asymmetric obstruction due to the opposite building part.

USE OF ARTIFICIAL LIGHTING

The results concerning the use of artificial lighting in the monitored office are exemplarily shown in fig. 4 for the first week in July 1990. During that week, the weather was sunny and warm. The figure illustrates the manual switch-on/off characteristics of the lamp circuits. From this figure more or less regular patterns can be recognised.

In lamp group I, which is closest to the west window facing the atrium, and in lamp group II in the back of the room, the lamps remain switched-on most of the day. In the specified week, both lamp groups were simultaneously switched-on and off. There is no indication that a specific quantity of light induces people to turn off the artificial lighting when enough daylight is available. This room seems not to be sufficiently daylit by the atrium.

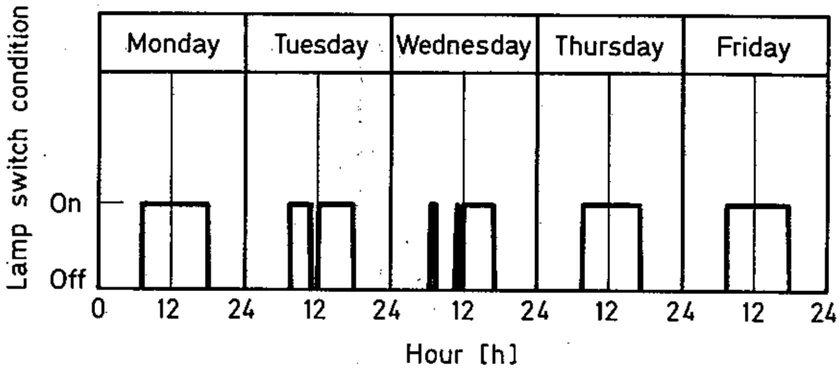


Fig. 4: Status of the artificial lighting in the monitored office of the Züblin building, Stuttgart, in the week of 2 to 6 July 1990.

The percentage of switched-on lamps in the 2 different zones is shown in fig. 5 for the entire monitoring period. From the figure below it can be seen that in both zones, the lamps were switched-on during 60 to 65 % of all hours during the monitoring period (weekends excluded).

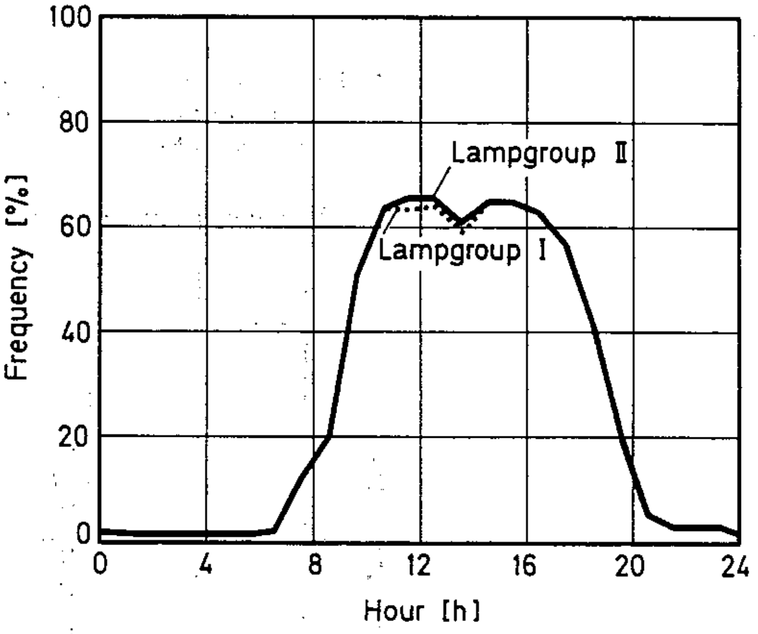


Fig. 5: Percentage of frequency of switched-on lamps in the 2 different zones for the whole monitoring period (weekends excluded).

Zone I (connected to the atrium) and zone II (in the back of the room) show surprisingly good agreement. An interesting point is the tendency that the lights are only switched-on. This happens in all zones during the day until the afternoon, and leads to higher internal heat gains due to lighting in the afternoon (when overheating can also occur!).

Figs. 6 and 7 show the switch-on resp. switch-off frequencies of both lamp groups for the whole monitoring period (weekend excluded).

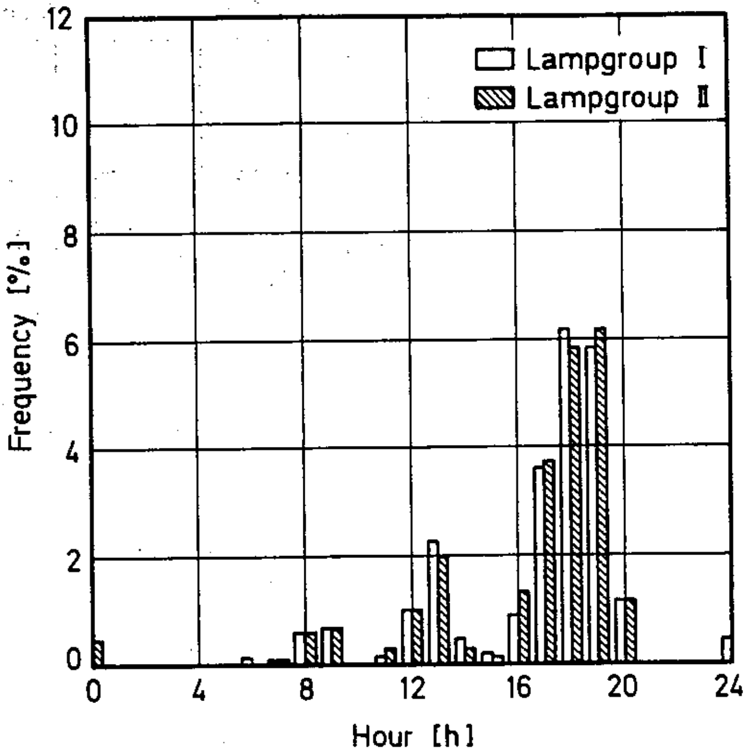


Fig. 6: Hourly switch-on frequency of lamp groups I and II in the Züblin building, Stuttgart, for the whole monitoring period in 1990.

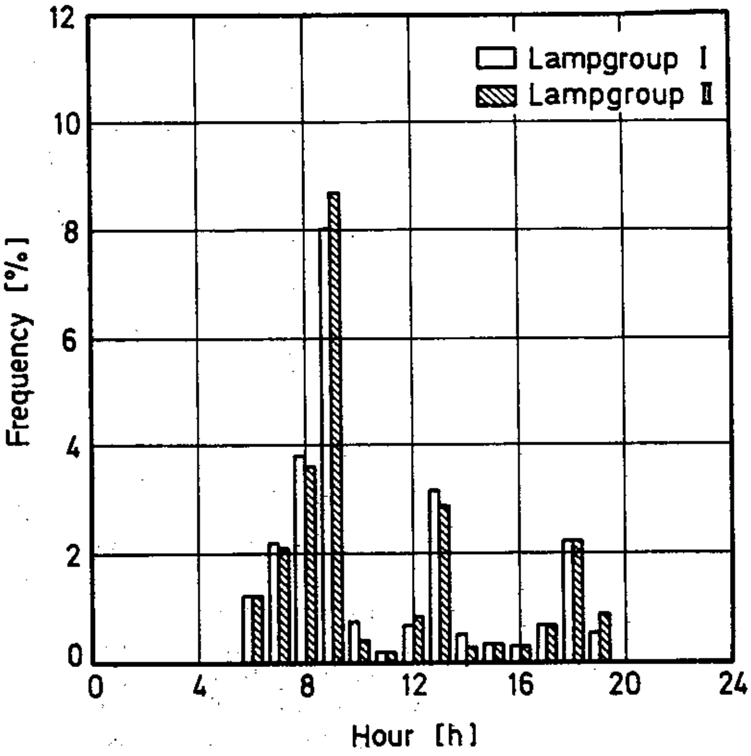


Fig. 7: Hourly switch-off frequency of lamp groups I and II in the Züblin building, Stuttgart, for the whole monitoring period in 1990.

Clearly, from the figures above, it can be deduced that artificial light is mainly switched-on three times during the day, namely in the morning, after lunch, and in the afternoon, whereas it is turned off before lunch and mainly in the afternoon. This means that in the monitored office, the users do not care very much about wasted lighting energy; although they turn off the light during lunch, they do not turn it off when the available quantity of daylight is adequate. On arriving at the office, the occupants consider whether they need additional light at this time. During the day, more and more artificial light is being turned on, particularly in the afternoon when daylight drops and the occupants recognise that daylight gets poor, unless they have already turned on the light.

Conclusion

Manual lamp control and use of shading devices in an office room were investigated over a period of 26 weeks in summer until winter 1990 in the Züblin building, Stuttgart.

From the measurements it can be concluded that artificial lighting is switched-on in office rooms for the major part of the working day. In zones which are daylit through the connected atrium, the light was switched-on during app. 65 % of all monitored working hours.

During the day, more and more light is switched-on mainly in three periods per day: in the morning, when the work starts, after lunch and in the afternoon. Light is sometimes switched-off after lunch, but mainly in the evening.

From the above, the general conclusion can be drawn that frequently manual light control does not lead to adequate, energy-efficient use of lighting systems. The potential for measures to decrease the energy used for lighting and cooling in buildings is worth a thorough examination in the future.

This investigation was funded by the German Ministry of Research and Technology in the framework of the German participation in the IEA-TASK XI project.

References:

[1] Base Case Studies Report
IEA-TASK XI

[2] German Participation in the IEA-TASK XI Project. National Report. Stuttgart (1991)

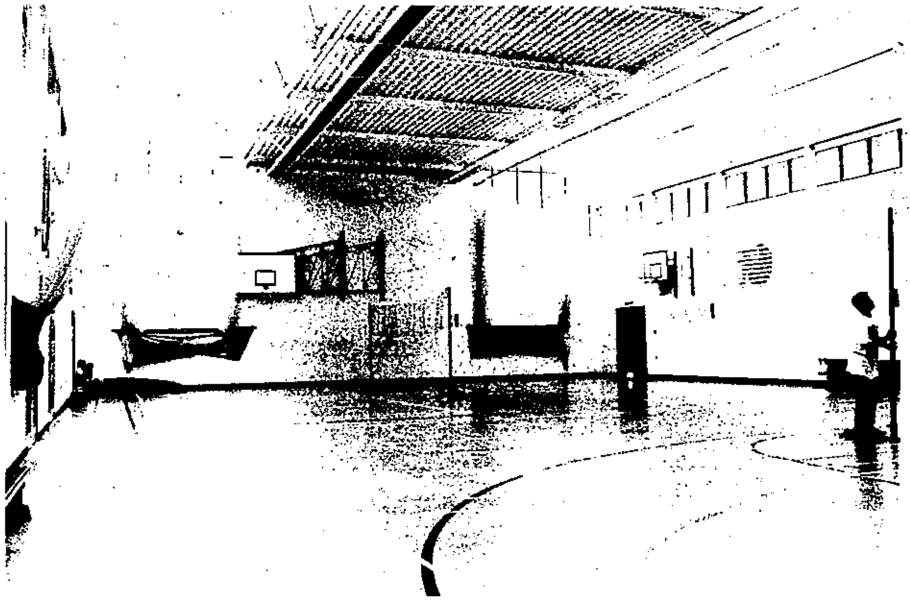
MOUNTBATTEN AND BRUNE PARK SPORTS HALLS

J.Palmer, R.Watkins, A.Seager, P.Shaw
Databuild Ltd.

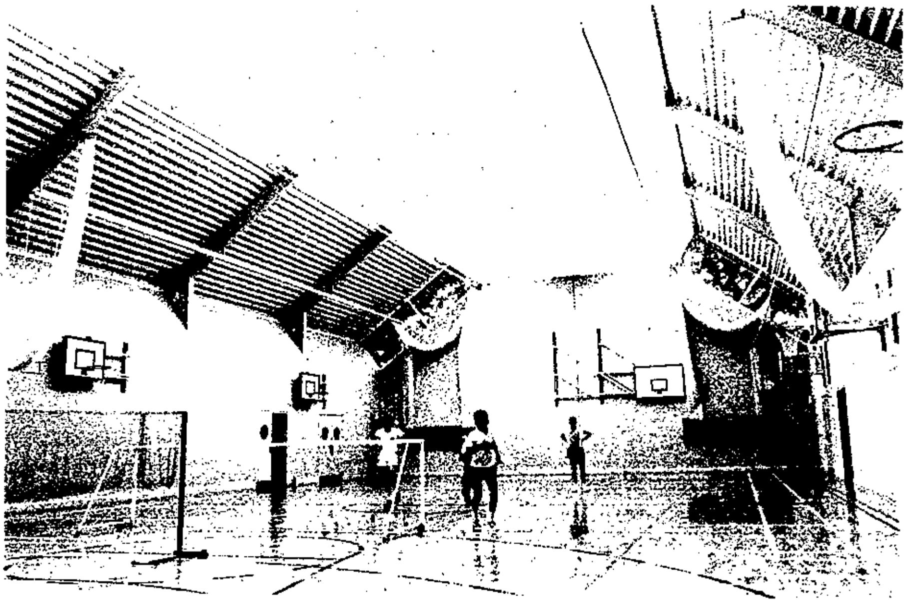
INTRODUCTION

This advanced case study reports on two daylit sports-halls in Hampshire, England; Mountbatten and Brune Park. Both sports-halls reflect the philosophy of the Hampshire County Council in their use of daylighting. The means chosen reveal a clearly articulated approach to the provision of toplighting to the sports-halls, and the two halls also show the development of the techniques used. There is a clear desire to retreat from sports-halls being an enclosed box solely lit by electric lighting. To study the success of these designs they have been compared by their performance in responding to daylight.

MOUNTBATTEN SPORTS HALL



BRUNE PARK SPORTS HALL



BUILDING DESCRIPTION

Both sports halls are situated at secondary schools and have their primary role as a space for physical education activity for school children. Out of school hours, both sports halls are used by the local community for a variety of events. Mountbatten has a community office attached to it and provides for a more casual user's needs. Brune Park accepts only regular bookings from clubs.

Both sports halls are rectangular and provide the same playing area of 30m by 16m (480 m^2). The main difference in form lies in the roof shape. Both buildings have a steel frame construction.

Mountbatten

Mountbatten sports hall is located at Mountbatten Secondary School, Romsey, and is about 8 miles north west of Southampton, England

Mountbatten sports hall has two parallel ridge roofs running north south with a lower flat roof between them. The inward face of each roof has a continuous transparent rooflight 1.9m wide. There is glass at high level along most of the perimeter of the building, but this is covered with extensive eaves over-hang. It has outer brick cladding and inner blockwork (with insulation between) with traditional tiled roof-work on its outer faces and corrugated double-layer plastic sheeting on the inner ones. Light coloured sloping walls at high level aid the distribution of the incoming light (and artificial light). The reflectivity of the floor is 37%.

The hall has artificial lighting provided by two lengths of fluorescent lights mounted on trays and shining upwards towards the ceiling; lighting is by reflection only. Installed capacity is 12.6kW made up of 180 x 70W tubes. It has a lighting control system. At either end of the hall are activity sensors and internal light-level sensors. These are designed to work as follows. The artificial lighting is provided in two distributed circuits (A and B) of similar rating. The photoelectric sensors only allow both circuits to be on if the *internal* light level is below a certain threshold - otherwise circuit A will be disabled. Similarly circuit B will be disabled if the light level exceeds a second higher threshold. The activity sensors will attempt to turn on or keep on the lights on for five minutes whenever there is activity, i.e movement, in the hall. It has space heating provided by conventional gas boilers providing hot water to ceiling radiant panels. The changing rooms are in an adjacent part of the school and there is essentially no provision for hot water use in the sports hall. There are two three-speed electric extract fans at high level to remove excess heat.

Brune Park

Brune Park sports hall is located at Brune Park Secondary School, Gosport, and is about 15 miles south east of Southampton, England.

Brune Park sports hall has a single ridge running north south. The roof forms a continuous curve over the ridge. On either side of the ridge are continuous strip roof lights 1.8m wide. The gable ends have glass at their edges and this continues round to the apex of the roof. There is no glass along the sides of the building. Brune Park has corrugated metal cladding externally and internally (with insulation between) and plastic double-layer roof-lights. All glazing is double. Both gable ends have brick cladding, but the north end has more glass than the south end. Brune Park uses a sail cloth to diffuse the daylight (and artificial light). The reflectivity of the floor is 45%.

The hall has artificial lighting provided by 33 x 400W lamps (13.2kW total) suspended beneath the roof at high level. These shine down through a sail cloth which is spread across the whole hall at high level. Brune Park has no lighting control system. It employs manual key switching. Two condensing boilers providing hot water to underfloor plastic pipes. Either side of the hall are changing rooms which have shower facilities etc. provided with hot water from a gas boiler. Air is extracted from the (windowless) changing rooms and nearby weight-training rooms through a system of ducts. This is operated by thermostat.

EVALUATION LEVEL

The evaluation of the buildings has two objectives. In the first place it is necessary to establish if the design has succeeded in providing a sufficient and suitable supply of daylight to the required spaces. Then secondly, it is necessary to establish if this daylight is being satisfactorily exploited to replaced electric lighting.

In order to assess the degree to which the buildings meet these objectives, measurements have been made of the relevant parameters.

MEASUREMENTS

To assess the provision of daylight in the sports halls measurements of daylight factors have been made. The standard technique for measuring daylight factors has been followed and the results of these are given below.

To establish whether the daylight availability influenced the use of electric lighting long term measurements are required. In order to do this the following were measured: horizontal global solar radiation, internal light levels, and electricity consumption. These parameters were logged at 15 minute intervals so providing a detailed measure of performance. The light level that is reported here is that as registered on light cells viewing vertically down from the ceiling of the halls. Other more conventional methods of measurement, such as the horizontal illuminance at working height, were not possible in this situation. The halls were in almost continuous use for sporting activities such as football and badminton, sensors at conventional positions were not feasible. Later analysis will attempt to relate the measured values to more typical figures by calibrations taken on site.

To ensure that all climatic conditions were covered the monitoring period for these parameters extended to twelve months. The following analysis has taken a relevant section of this period for analysis.

FINDINGS

Daylight Factors

All daylight factor measurements were taken at a height of two metres and on a one metre grid across the halls. Recommended illuminance for sports halls varies with the kind of sport and the degree of seriousness with which it is being played. For multi-purpose halls this about 300 lux, rising to 500 to 750 lux for fast moving competitive sports.[1,2]

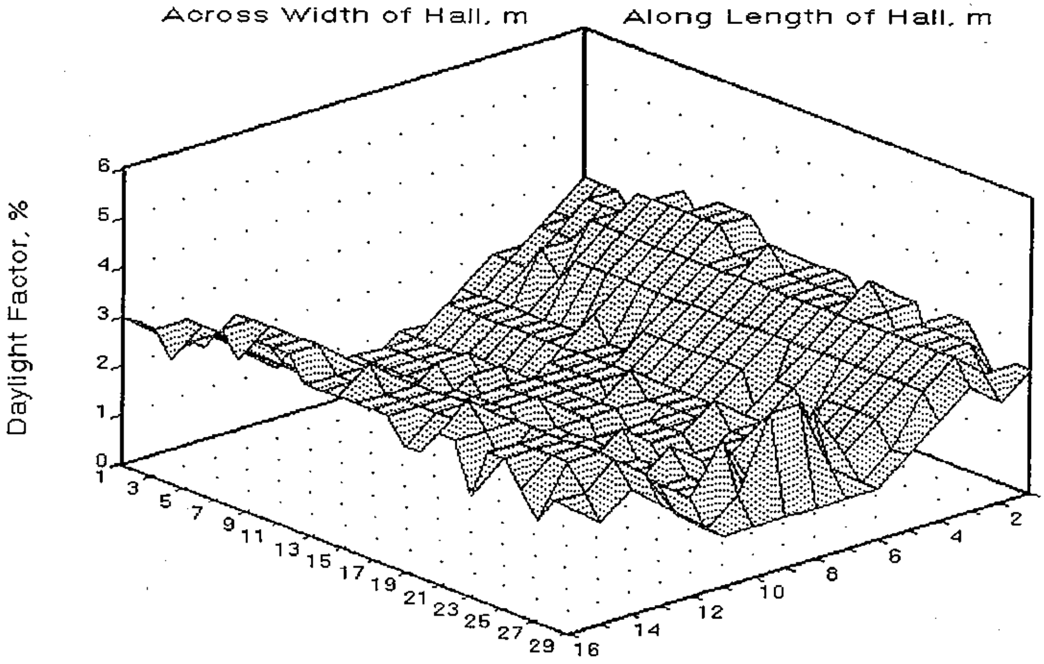
Mountbatten

The 3% daylight factors recorded adjacent to the walls indicate a good supply of daylight, as was intended. The daylight factor of 1% at the centre of the hall under the flat portion of the roof is less satisfactory. However, it should be compared with a non-daylit hall. The average daylight factor of 2.1% shows the space to be less well daylit than is suggested by the CIBSE Applications Manual, Window Design[3], which suggests an average factor of 5% with a minimum of 2.5%. However, these figures are for side-lit spaces and implicitly allow for the lack of uniformity in illuminance found in such lighting. The greater the contrast in illuminance in a space the greater the need to meet these minimum daylight factors if the switching on of lights is to be avoided. Figure 1 shows the distribution of the daylighting within the hall.

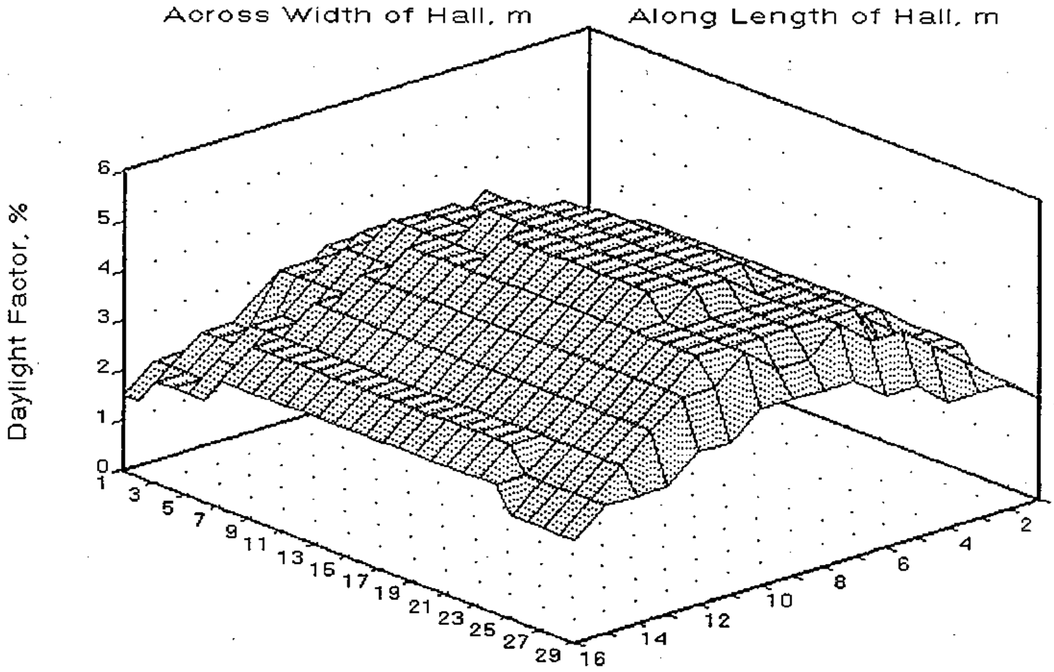
Brune Park

The 5% daylight factors at the centre of the hall indicate a very good level of daylighting and the lowest level of 2.5% is still adequate. The average daylight factor is 3.5%, and whilst this is good it is below the 5% required to avoid occupants using artificial light. In Brune Park the data for only half of the hall were obtained (owing to equipment failure). The values quoted above refer to these data but the image in Figure 2 assumes the

MOUNTBATTEN SPORTS HALL
DAYLIGHT FACTORS



BRUNE PARK SPORTS HALL
DAYLIGHT FACTORS



physical symmetry of the hall gives rise to a daylight factor symmetry along the length of the hall. The distribution of the lighting is however far superior to that of Mountbatten. This is achieved by the white sail cloth that is interposed between the roof-lights and the hall below. This material reduces light transmission downwards by 40%, but is responsible for a much more uniform lighting below. If it weren't there, the average daylight factor might be nearer 6%, but illuminance would be more variable and the risk of glare increased significantly.

Electric Lighting Use

The pattern of use of electric lighting is considered here by reference to the measured light levels on the hanging sensors at high level. When no electric lighting is in use the illuminance will clearly be a function only of the solar radiation. When electric lighting is supplementing daylight the relationship between solar radiation and internal light level is shifted up by a constant. In considering Figures 3 and 4, the actual mean illumination levels in the halls can be approximately obtained by doubling the measured reflected levels. The floor reflects just under half the incident light.

The quarter-hourly data for both Figures 3 and 4 are taken from October 1989 to September 1990, Mondays to Fridays, 09.00 to 17.00, discounting the summer. This is 211 days of data.

Mountbatten

From Figure 3, which shows the luminance measured as indicated above, there are several lines expressing the illuminance as a function of solar radiation. One of these clearly goes through the origin and indicates the situation when no artificial lighting is in use. The other lines are offset from the origin and show the light levels when electric lighting was in use. The distribution of points would tend to illustrate the three steps (A, B, A+B) in the control of the electric lighting. From this the visual appearance is of a considerable number of times when the lights are used even when the external solar radiation is sufficiently high to almost guarantee that little lighting is needed.

Brune Park

Considering the same plot but for Brune Park, Figure 4 shows a similar form. There is a more distinct pattern to the data, than in Mountbatten, because there was no automatic control of the lighting circuits at this hall. The two lines indicated show the luminance levels with and without the electric lighting. The data suggest much less use of electric lighting at higher levels of solar radiation than seen in Mountbatten. By analysis of the occurrence of lighting use there is a significant difference with Brune Park lights on for 23% of this time and Mountbatten lights on for 76% of the quarter hour periods.

The Brune Park data show that good levels of illumination and uniformity combine to reduce the occupants' desire to switch lights on.

Figure 3

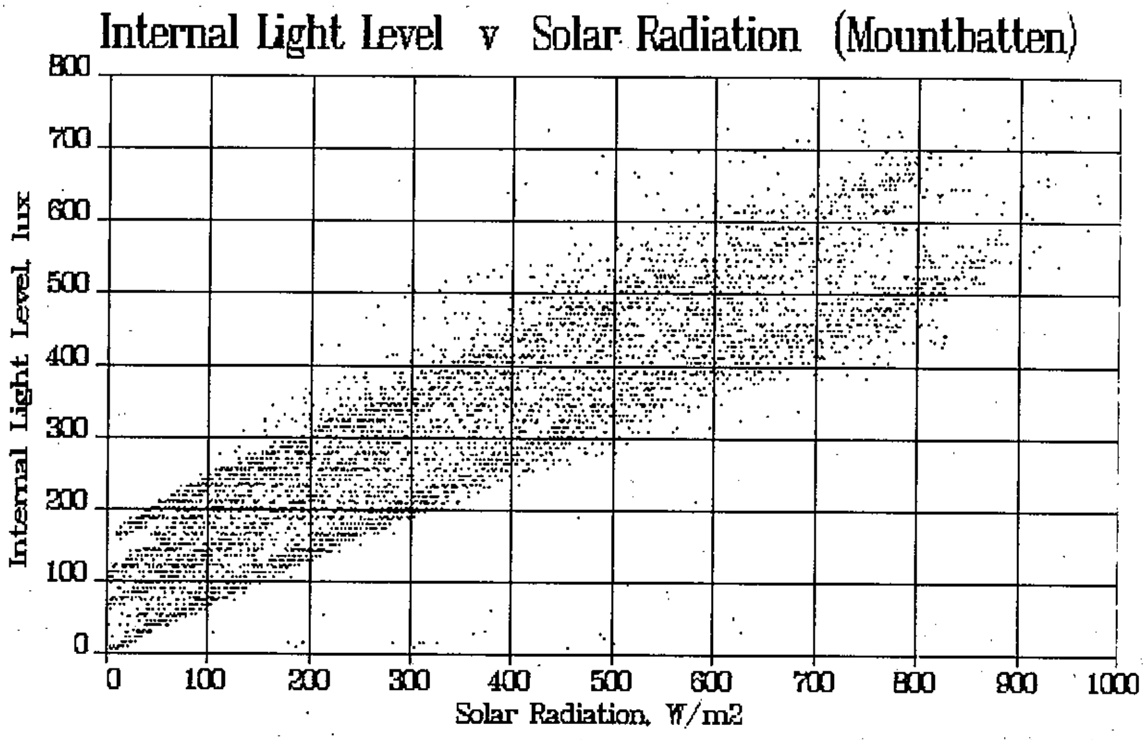
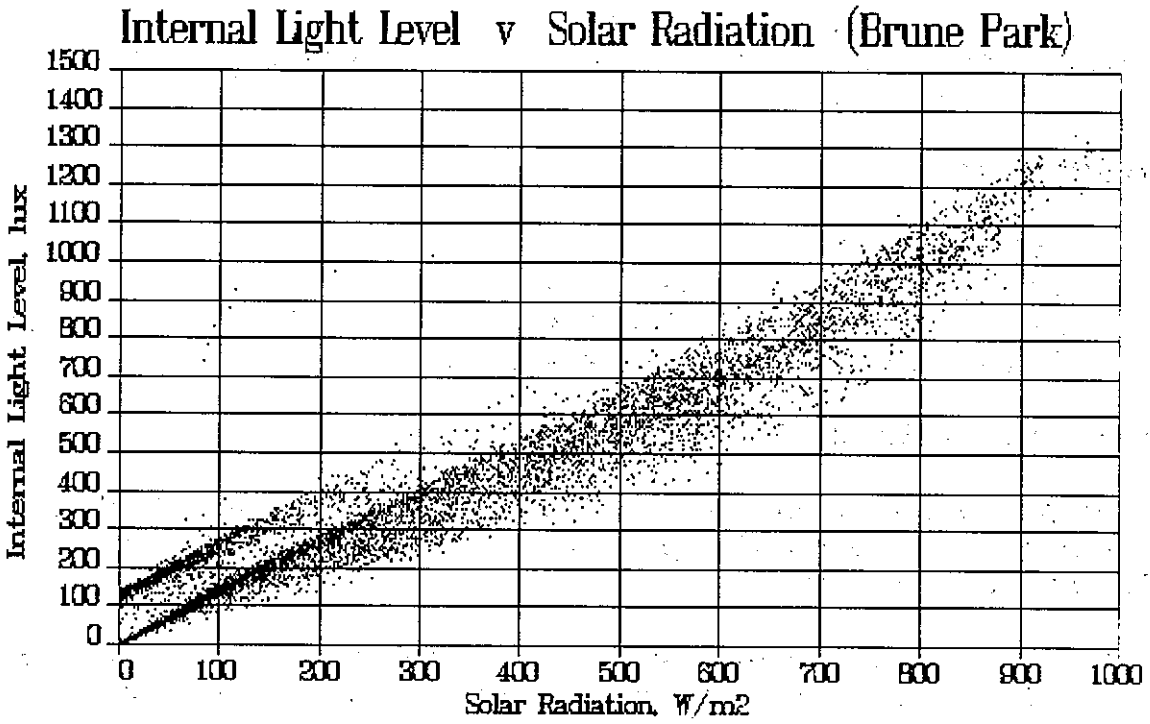


Figure 4



CONCLUSIONS

The measurements show that for a large proportion of the time natural daylight gives rise to sufficient illuminance in both sports halls for the activities they are used for in school hours. The designs are successful in providing illumination by daylight; their performance should be compared to the lighting needs of sports halls with no windows - a common design.

The quality of the illumination differs between the halls; Brune Park's use of a diffusing awning is effective in providing a smooth variation in lighting level.

The degree to which daylight is allowed to displace electric lighting varies considerably between the halls, and for different reasons.

Mountbatten sports hall has, in practice, a control system which switches on lights when people come into the hall and switches them off when they leave - regardless of ambient light levels.

Brune Park sports hall has no automatic control system. In fact the lights can only be turned on by using a key switch - and there is only one key. This fact probably deters the use of the lights. However, it also means that lights may be left on when the hall is unattended.

When using daylight to displace electric lighting it is essential to provide controls which assist the occupants to realise their needs, but at the same time limit the consumption of electric lighting to a minimum. This is, in practice, difficult to achieve. It is perhaps surprising that in this case study it is the sports hall with only manual control (Brune Park) that has performed better than the one with electronic occupancy and light level sensors (Mountbatten). This reflects the exceptionally uniform daylit space at Brune Park.

REFERENCES

1. IES Code, 1977
2. The Sports Council, Energy Data Sheet No. 15.
3. Application Manual, Window Design, 1987, The Chartered Institution of Building Services Engineers.

ACKNOWLEDGEMENTS

Both sports halls are being assessed as subjects of the Energy Performance Assessments in the U.K.'s passive solar research programme of the Department of Energy.

The authors would like to thank the users and owners of the sports halls for their co-operation and helpfulness in the monitoring of these buildings.

SOUTH STAFFORDSHIRE WATER COMPANY

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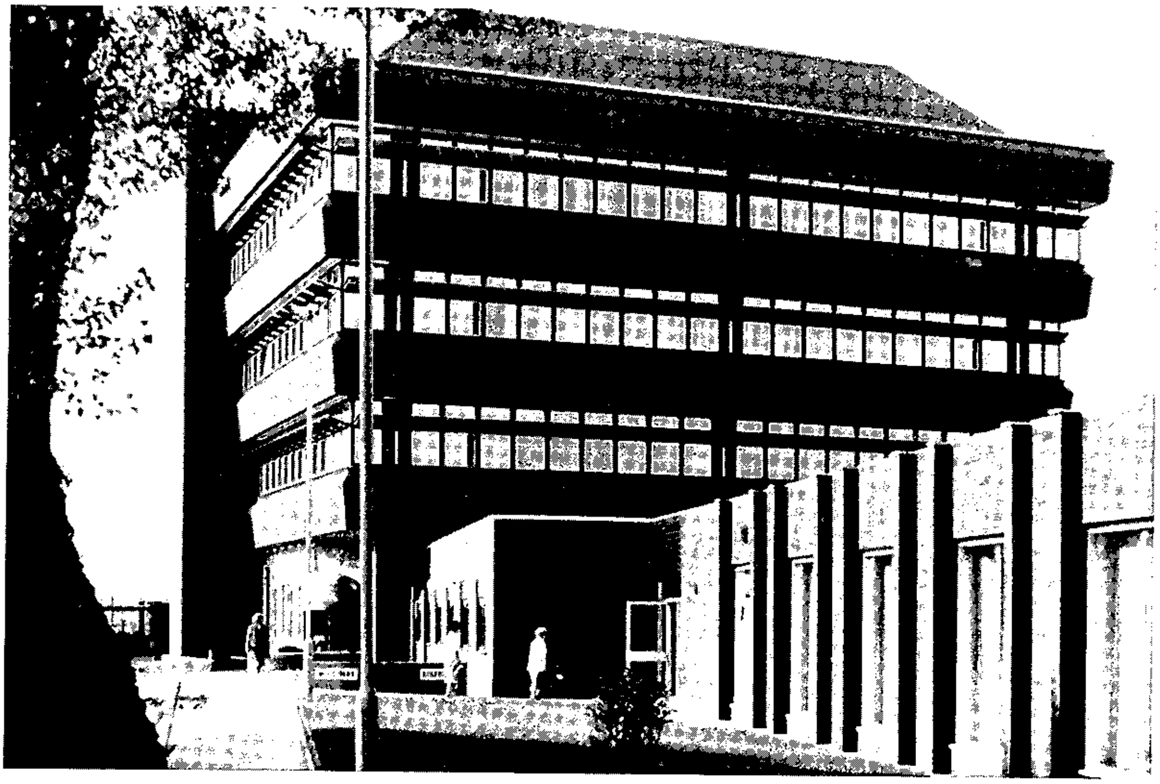
Datasbuild Ltd.



ABSTRACT

The 3 200m² four storey building utilises light shelves to provide shading from summer solar gain and to improve daylight distribution in rooms. The shelves allow large areas of glazing, with heat losses reduced by the low emissivity double glazing.

The results from 12 months monitoring confirm that the light shelves modify, rather than redistribute, daylight, with a consequent improvement in uniformity. Uniformity is improved at eye heights relative to desk height and it is speculated that this effect may reduce demand for electric lighting. The automatic control system appears to inhibit optimum energy savings.

As part of a US/UK bilateral agreement monitored data was used to validate the Daylight Performance Evaluation Methodology devised by Lawrence Berkeley Laboratory. Results showed a very good correlation between modelled and measured data.

INTRODUCTION

The 1981 brief from the South Staffordshire Water Company called for about 3000 m^2 of office space for the relocation of staff and the mainframe computer to Walsall. The relocation had to meet a payback criterion of 7 years. Reduced fuel and maintenance costs were recognised as an element in this. The developed brief explicitly called for a low energy building for which additional capital expenditure would be allowed within the overall cost constraints.

Initial energy studies confirmed that the cost of electric lighting could be of the same order as the gas space heating, other considerations also suggested that the advantages of deep planning were insufficient to offset the capital and running cost penalties associated with mechanical ventilation. These considerations together with the client's quest for a good working environment and energy efficiency caused natural ventilation and daylighting to emerge as high priorities in design.

The building was subjected to an "Energy Performance Assessment" on behalf of the Energy Technology Support Unit for the Department of Energy, which considered the performance of the whole building as well as the passive solar features. Issues of energy, cost and amenity were evaluated over 12 months.

The evaluation of daylight displaced electric lighting has been the subject of a collaborative project with the Lawrence Berkeley Laboratory, USA, whereby a method for evaluating long term lighting performance from short term measurement has been developed and tested.

SITE & LOCATION

The site is an industrial area of scattered 1 and 2 level buildings to the north of Walsall which itself is about 15 km north-west of Birmingham in the Midlands region of the United Kingdom.

Site Data
Latitude - 52.6°N
Altitude - 162 m

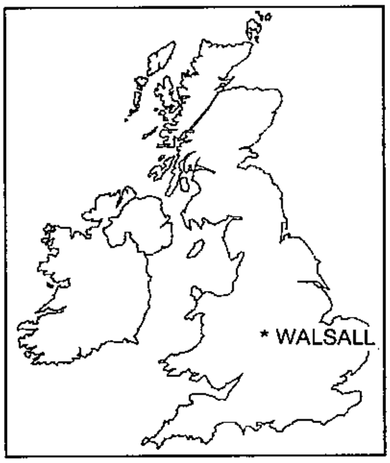


Fig 1

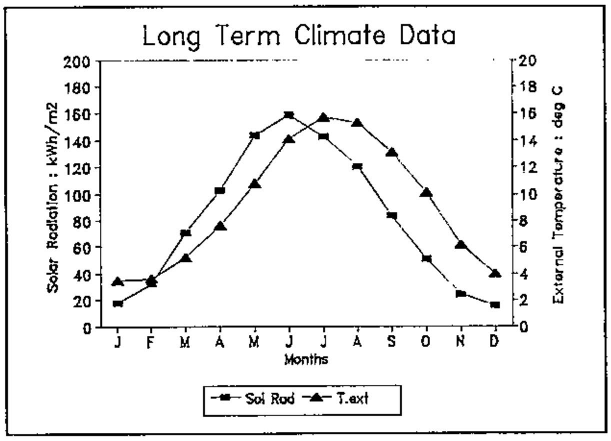


Fig 2

Oct to Apr inclusive		Annual
Degree Days (base 20)	: 2 452	4 094
Sol Rad G_H MJ/m^2	: 1 140	3 463
Actual Sun Hours	: 508	

BUILDING FORM

The building is a four storey building housing 3200 m^2 of office space and has a design occupancy of 160. The four storeys are ground floor with reception and three floors of offices each with a continuous fenestration. There is also a mezzanine and an attic. The buildings basic shape is that of a compact cube in which each floor overhangs the one below it by about 0.6m this not only creates increasingly greater floor areas but also provides shading to the windows. The building is attached to the old single storey office block at ground floor and mezzanine level. In plan the offices are on the perimeter and wrap around a concrete central core in a U shape; the open end of the U houses the main staircase, lift and circulation areas. The central core of the building contains the fire escape stairway, toilets and services. Located to the west and north are separate 2-storey buildings, the new building is unobstructed in other directions.

Dimensions :
Floor to ceiling height : 3m

Size :
Gross - 3833m^2
Heated - 3208m^2

Floor Areas : m^2
Ground Floor - 985
inc Comp Suite - (170)
Mezzanine - 287
First Floor - 595 → Heated
Second Floor - 645
Third Floor - 696
Attic Space - 625 → Un-heated

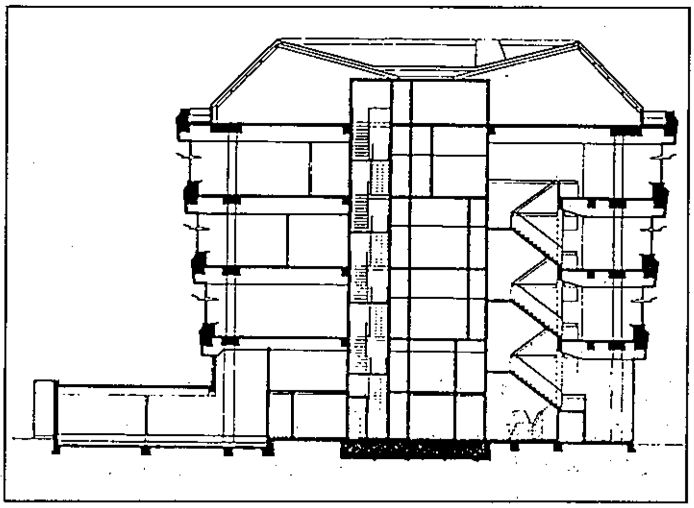


Fig 3

BUILDING CONSTRUCTION

It is an in-situ concrete frame with reinforced concrete cladding panels and a facing brick finish. Bad ground conditions required a complex sub structure with grouting to 35m depth and 128 piles.

High insulation standards are used throughout, the ground floor incorporates 75mm polystyrene, the walls include 100mm ureaformaldehyde and insulating blocks, the overhangs included spray on insulation (150mm polyisocyanurate) against cold bridges, the pitched roof is insulated in the attic floor with 100mm polystyrene. Windows are low emissivity, argon filled double glazing in high performance UPVC frames of low U value and negligible air permeability.

U-values :
floor - 0.35 W/m2
wall - 0.20 W/m2
window - 1.60 W/m2
frames - 1.60 W/m2

Envelope Heat Loss : kW/K
Transmission - 2.1
Infiltration/ventilation - 3.0

Glazing Properties :
Double glazed , low emissivity,
argon filled (12mm).
U - Value - 1.6 W/(m^2 K)
Daylight Trans - 60 %
Solar Trans' - 59 %
or if reversed - 69 %

BUILDING SERVICES

BUILDING ENERGY MANAGEMENT SYSTEM.

The mechanical services are controlled by a Landis and Gyr energy management computer, model "Visonik-4000". The system performs time and photo-electric control of lighting with local manual override; heating ventilation and air conditioning control, and plant condition monitoring. The B.E.M.S. also controls the fire alarm and security systems and logs fuel consumption and temperatures throughout the building.

SPACE HEATING.

The boiler plant comprises 3 natural gas-fired Hamworthy modular boilers which supply low pressure hot water (LPHW) to constant and variable temperature systems.

The variable temperature system provides space heating through radiators to the upper floors, office and stair landings. It comprises a weather compensated radiator system with four zones per floor. All zones are controlled by thermostats through the central energy management system and radiators have thermostatic valves.

Constant temperature hot water is supplied to the various air handling units heater batteries in the toilet (and directors kitchen), the hot water calorifier, the entrance foyer fan convectors (ceiling mounted), and to the ground floor radiators which are located under the windows.

VENTILATION.

The perimeter offices and circulation areas are designed to be passively ventilated and as such have no installed mechanical ventilation or air conditioning. There are certain areas which are air conditioned though, these being, the computer room and its peripheral offices, the toilet areas and kitchens. The air conditioning unit is located within the ground floor computer plantroom.

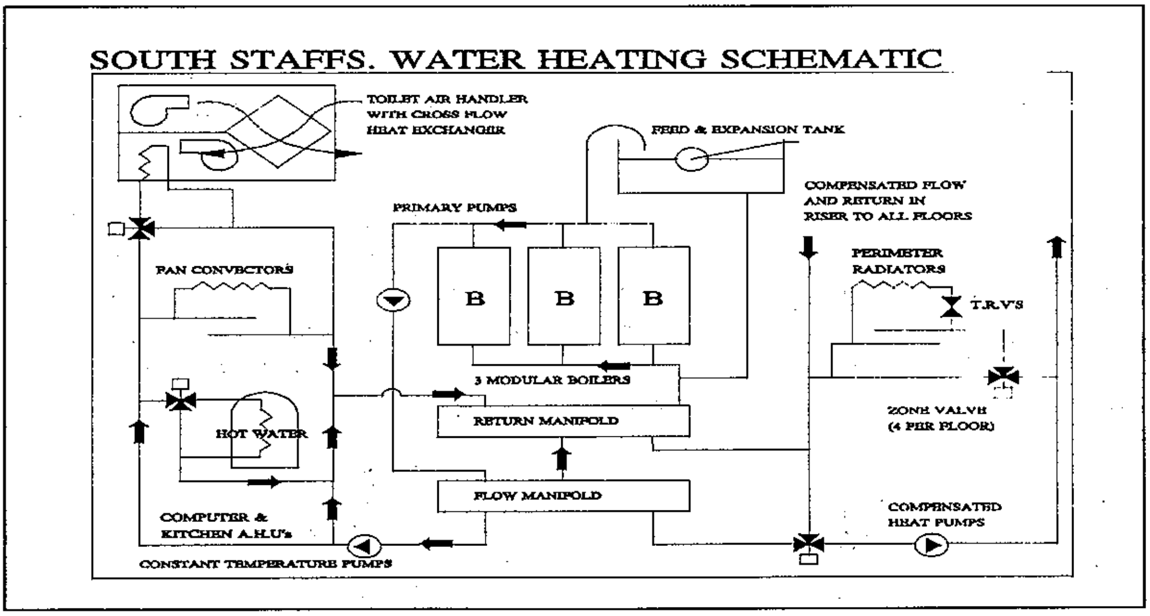


Fig 4

LIGHTING.

Lighting in offices comprises recessed ceiling and wall mounted fluorescent luminaires, providing 350 lux with an installed capacity of 10 W/m^2. Task lights (at 16 W/desk) are provided were higher light levels are required.

Office ceiling lights on all floors are automatically controlled via the B.E.M.S. The controllers use time of day and information from roof mounted photo electric cells (2 on each facade) to determine when manual switching ON is allowed. This logic is also used to automatically turn OFF luminaires when it is determined that they are not required. Lights can be turned off at any time. The luminaires are banded into banks depending on their position within the room, each bank is on a separate circuit and is switched as a single unit. Some luminaires are on constantly during working hours to provide a minimum level of background (or safety) lighting.

Lighting
Installed Capacity :
Offices; Ceiling - 10 W/m^2
Task - 16 W/desk

Design Condition :
Offices - 350 lux
Circulation - 250 lux

Ceiling Luminaires :
600mm recessed fittings each including three T8 linear fluorescent tubes (correlated colour temp 4000 K, colour rendering index Ra 85). Power use is 75 W per fitting.

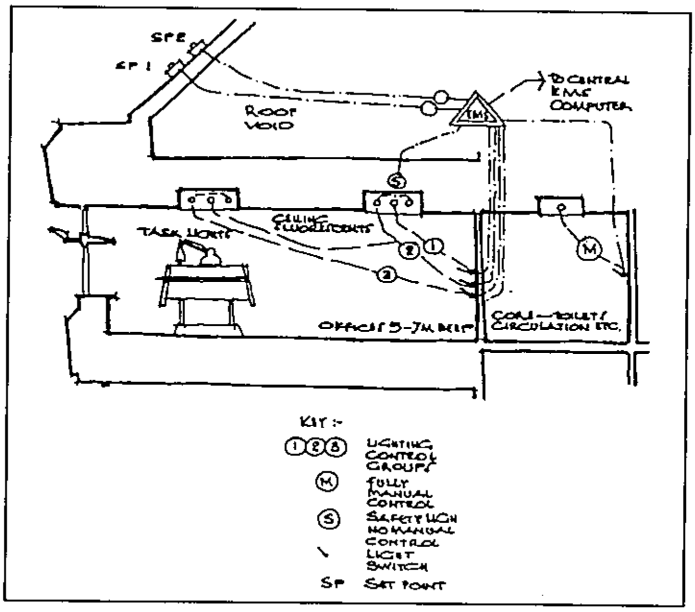


Fig 5

OTHER SERVICES.

Electric usage other than lighting includes; post sorting machinery, commensurate with the billing requirements for 1 million customers; lift operation and the general use of microcomputers and small appliances.

SOLAR FEATURE

The principal passive solar feature was the use of internal and external light shelves to enhance the natural lighting within the office spaces, thus reducing the necessity for artificial lighting. The light shelf design was developed from work done in the 1950's by the Nuffield Foundation Hospital Trust. The high level shelf (internal and external) acts as a solar shade to reduce light levels near to the window and would possibly increase light levels at the rear of rooms. The principal objective was to limit the admission of summer solar gains without large reductions in either winter solar gains or daylight to the rear of rooms. A deep concrete window sill at desk level was used as a high admittance solar absorber in an attempt to further smooth out summer peaks in solar heat gains. This was made of high reflectance to further enhance daylight.

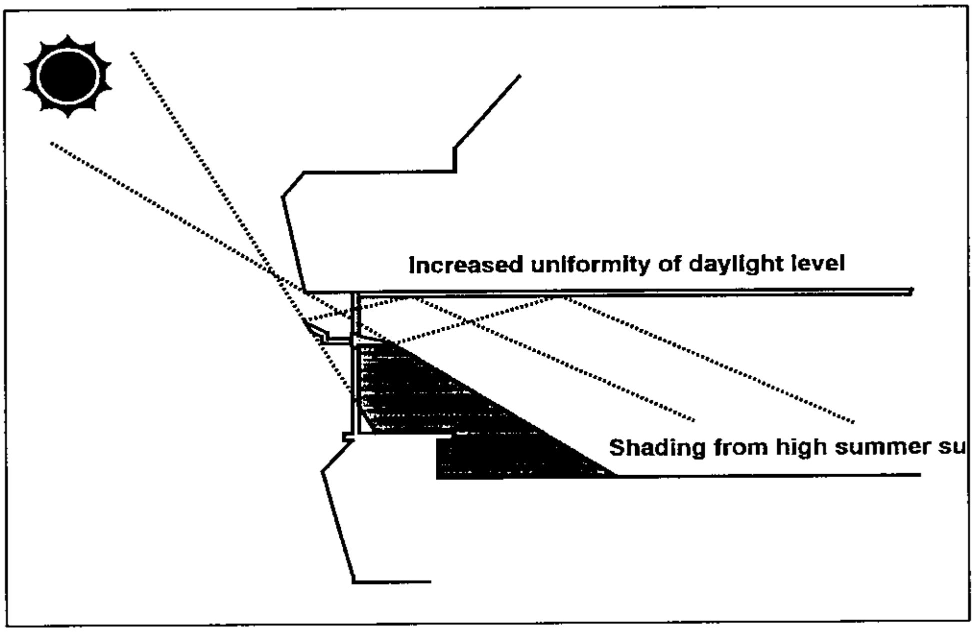


Fig 6 Passive solar strategy

BUILDING COST

The building is principally new build but includes some refurbishment in the link with the existing building. The cost (£467/m² gross floor area) compares well with typical costs for similar offices (£420 to £500/m²) and suggests that the energy saving features have been incorporated at little extra cost. Analysis of the costs indicates that the window shading and shelf systems consumed about 3% of the total cost and the high performance windows accounted for a further 8%.

EVALUATION METHODS

The objectives of monitoring the building were to determine how well the building performs as a whole compared with other buildings. More importantly though was to determine how well the passive solar feature worked in terms of reducing the energy demand and improving the working environment.

In a joint US/UK venture monitored data from (2) and (3) below were used to validate the, then recently developed Daylight Performance Evaluation Methodology.

MONITORING

The monitoring of the building was performed in three stages :-

(1) Whole building...Low level monitoring of the building for a period of 12 months. This is to ascertain how effective the building, as a whole, is as a low energy building.

(2) Passive feature..Intensive monitoring, over 12 months, of the passive solar feature on the second floor to determine its' contribution to the overall performance.

(3) A one-time-test..Performed overnight to reduce the effect of external lighting, was made to calibrate the individual effects of the BEMS controlled electric lighting groups on the individual light sensors and power consumption on the second floor.

MODELLING

Daylight Performance Evaluation Methodology

The DPEM uses both mathematical simulation and measurement in order to identify the annual effectiveness of the daylighting system. Short term (one to four weeks) measurement of solar radiation (both global horizontal and diffuse), internal light levels and electric lighting power are made. Radiation data are converted, in the model, to lux via luminous efficacy, and in this instance but not essentially, the Superlite model is used to predict internal daylight factors. A night time test, (3) above, was used to split daylight and electric light levels.

These data are to be used to adjust mathematical models for daylight and lighting energy use in the selected spaces. The key relationships are the internal light levels as a function of daylight, and the electric lighting energy use as a function of internal illumination and lighting control strategy. These models once established and calibrated for a short period of monitoring are extrapolated using annual climate and building use data to yield annual performance data.

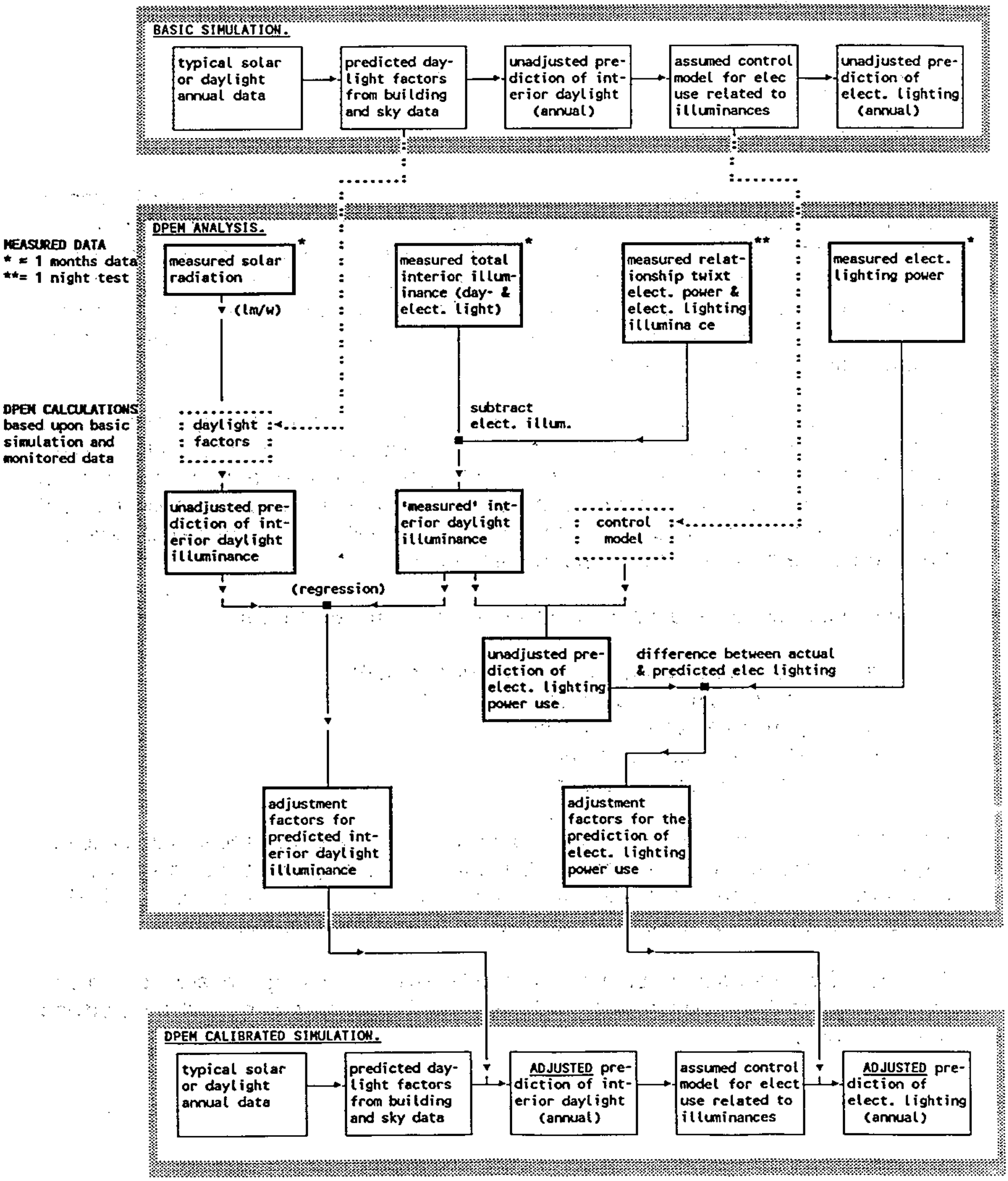
The computer model requires 5 input files, those being as follows.

a. measured events (hour or quarter hourly)
b. electric circuit groupings
c. power versus illumination
d. structured control model
e. annual hourly solar data

Besides the monitored data, specific building parameters are required for input into the daylight factors calculation engine (Superlite). These parameters are, building geometry, latitude, orientation and various surface reflectances. An idealized DPEM flow chart shown below details the required inputs and analysis stages.

The input for these files is obtained from intensive monitoring, observations made during visits to the building, talks with the buildings occupants, and by studying drawing plans.

Idealized DPEM flow structure



RESULTS

WHOLE BUILDING ENERGY AND ENVIRONMENT

All figures and observations are based on a monitoring period of 12 months from March 1987 to February 1988 inclusive. Space heating use has been normalized to local 20 year average degree day data.

FUEL USE

The actual delivered gas for the new office building alone could not be measured, as the boiler room also serves adjoining buildings. However, by using the derived system efficiency (57.5%)* and monitored energy use, an approximate figure for gas use for the new building was obtained.

FUEL TYPE	NORMALIZED DELIVERED FUEL (kWh pa)	
	Total	/m²
Gas	349 820	91
Electricity	143 410	37
Total	493 200	128

PSA Performance Indicators
Naturally Ventilated Offices < $5000m^2$

Whole Building Energy

	kWh/m^2 pa
Good	< 230
Fair	230 to 289
Poor	289 to 359
Very Poor	> 359

* The system efficiency was derived from the simple relationship between gas delivered to the boiler and the energy use of all of the functions serviced by it. The efficiency is quite low due in the main to services outside of the main building.

The total delivered energy of 128 kWh/m^2 pa (based on the gross floor area 3833 m^2) compares favourably with DoE PSA performance indicators for naturally ventilated offices (< $5000m^2$) where good is less than 230 kWh/m^2 pa.

DISAGGREGATED ENERGY USE

The delivered gas for the new office building alone could not be measured consequently the values below are for normalized actual energy uses within the new building. The major functions were obtained through direct monitoring. Some ancillary functions (ie DHW) were derived using information supplied by BRECSU for buildings of a similar size and type.

FUEL TYPE	FUNCTION	NORMALIZED ENERGY (kWh pa)	
		Total	/m²
Gas	Space Heating[1]	110 040	39
	Space Heating[2]	61 860	155
	Hot Water[2]	29 250	
Electricity	Lighting[3]	50 670	16
	Other Uses[4]	92 740	
Gas & Electricity Total[5]		344 560	90

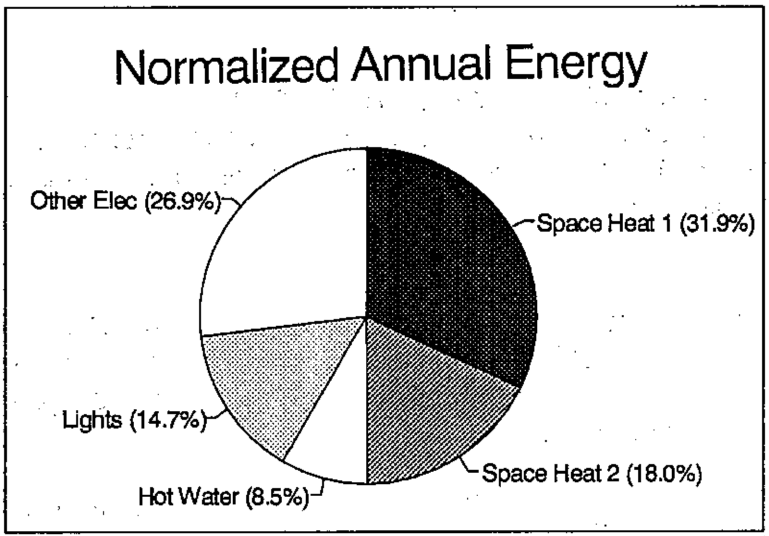


Fig 7

1 Space heating for the offices is provided by the variable temperature circuit, and is apportioned over 2808m^2 (building heated area minus the reception area and toilets.

2 Space heating for the reception area and toilets (400m^2), and domestic hot water are provided by the constant temperature circuit.

3 Lighting is apportioned over the heated floor area 3208 m^2 (all except the roof space).

4 Other electric uses include, lift and mail sorting machinery commensurate with 1¼ million customers, as well as the more normal photocopiers, vdu's and task lighting.

5 Total energy use within the building is apportioned over the gross floor area, 3833 m^2.

SPACE HEATING

Space heating, which maintains an average internal temperature of 20 to 21°C, has a low energy use with a short heating season Oct-April. The variable temperature heating system, which serves all offices and the upper floor stair landings, provides 39 kWh/m^2 pa to the perimeter radiators in these areas. In contrast the constant temperature system provides about 155 kWh/m^2 pa to the heaters and mechanical ventilation systems in the ground floor reception area and toilets. This is due in part to the higher air change rates. The average building use was 53 kWh/m^2 (equivalent to 92 kWh/m^2 delivered energy).

PSA Performance Indicators
Naturally Ventilated Offices < 5000m^2
Space Heating and DHW

	kWh/m^2 pa
Good	< 209
Fair	209 to 259
Poor	259 to 320
Very Poor	> 320

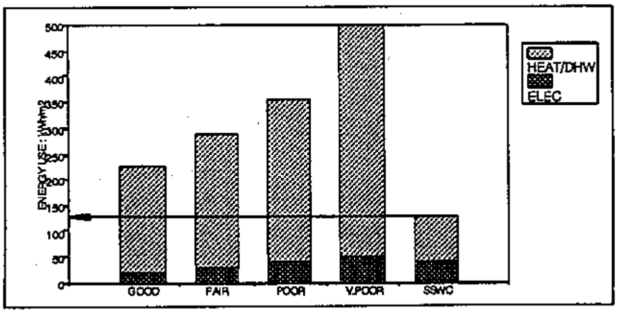


Fig 8 Comparison with performance indicators

LIGHTING

Lighting	kWh	kWh/m²
G & Mezz	12 280	10
1st floor	9 497	16
2nd floor	13 494	21
3rd floor	15 398	22
Other Elec	92 740	24

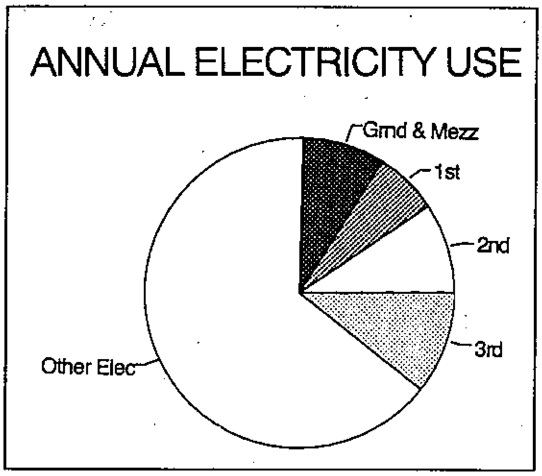


Fig 9

The areas used for the distribution of electric lighting on each floor are; Ground floor and Mezzanine 1272m^2, first floor 595m^2, second floor 645m^2, and third floor 696m^2, and all other uses 3833m^2.

The figure shows the annual distribution of electricity in terms of lighting on each floor and "other" uses. Electric lighting, when represented as a proportion of the whole building electricity usage, summates to only 35% of the total. The high level of other uses is due in the main to non-environmental demands such as, personal computers, which are common place throughout the building; mail sorting machinery commensurate with 1.25 million customers; and operation of the lift.

The varying levels of lighting consumption can be part explained by the increases in floor area as one ascends the building and the variation in use and occupancy levels on the various floors.

DETAILED ANALYSIS

Two second floor offices (344 and 135 m^2) were selected to provide representative spaces. Data were recorded from April to June 1987. Results detailed below are based upon the southerly facing office.

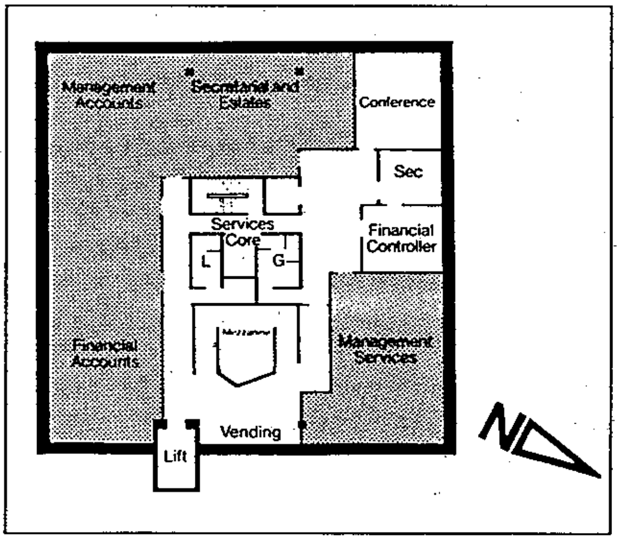


Fig 10 2nd floor offices

TIME SERIES

Comparisons of typical weekdays in April are shown. Data used are averages of electricity for lighting and internal light levels within the 2nd floor south-east monitored office and total horizontal and diffuse solar radiation.

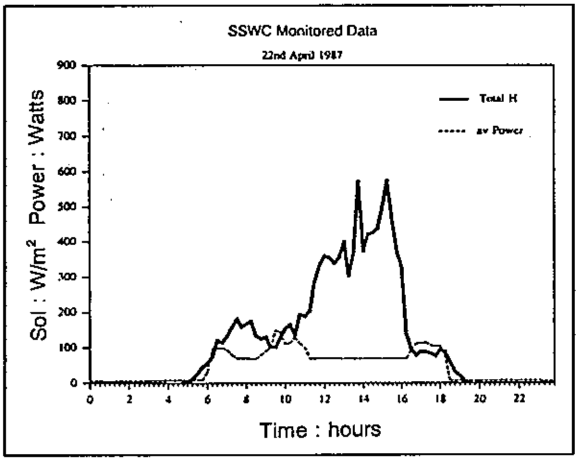


Fig 11 Overcast day

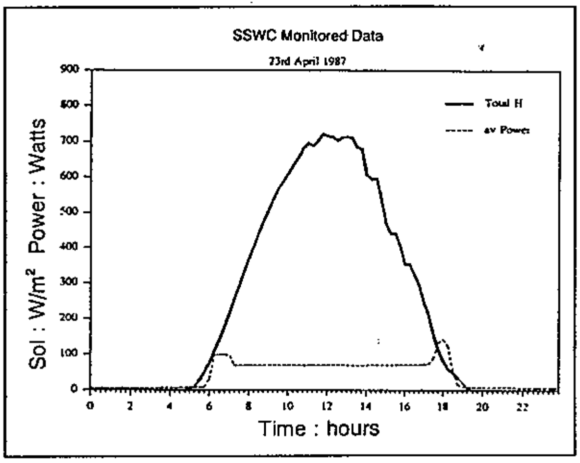


Fig 12 Sunny day

The graphs illustrate how lighting energy and internal light level responds to the available solar resource. From these it can be seen quite clearly that on both days supplemental electric lighting is required for the first thing in the morning and last thing at night. During the overcast day (22nd April) the lighting power reacts to alterations in the available total horizontal solar radiation throughout the day. Both the overcast and the sunny day show that their exists a high base load of electric lighting use irrespective of the external light level.

The base load is a result of the lighting control software, which, in order to provide safety lighting, allows for wall lights and one luminaire in each of the groups of ceiling mounted lights at the rear of the room to be on permanently during office hours, irrespective of available daylight and occupant wishes. It is important that safety lighting is provided although the level provided in this building is excessive and inhibits the full realization of the daylighting strategy.

Although the BEMS maintains a control over the lighting, it is not possible to know the full extent of the influence of the BEMS over the lighting power used during this (or any other) period. This is due in part to the fact that the actual set points of the light controlling photocells is unknown due to the nature of the set up procedure. Additionally, although the BEMS may at any time be permitting the lights to be switched on, the occupants may not feel that there is a requirement for additional artificial ambient lighting. This is indicated on the overcast day (22nd April) when the average internal lux only met or exceeded the design level of 350lux for 29% of the working day and there was no additional lighting used until the internal light level dropped to about 175 lux with a corresponding external light level of around 120 W/m². This indicates that the occupants were satisfied with (or tolerant of) light levels which were lower than the design level. The 22nd april however was a particularly dull day and further monitored results show that average light level within the office during working hours in April were in excess of 500 lux.

The figure for the dull day shows that at both times when additional ambient electric lighting was called for the external light level was around 120 W/m^2, this suggests that this may be the set point below which the BEMS allows switching ON of the lights.

STATISTICAL

The points indicated in the "time series" analysis are also apparent in the results of the statistical analysis. The purpose of this analysis was to ascertain the relationship between the level of electric lighting used in the office spaces monitored and the available external solar radiation. The analysis was performed on quarter hourly data recorded throughout April and May 1987.

The figure shows again that a distinct base level of lighting exists at around 80W for average lighting circuits. This base level is effective when the external solar radiation exceeds 120 W/m^2. Below this figure the lighting power is seen to increases, which is in agreement with the information displayed on the previous graph and is indicative of supplemental lights been allowed to be turned on. It is also apparent that the full lighting load is very rarely required, this indicates that the daylighting strategy is working well. The monitored value for lighting power during all working days in April and May is only 30% of the possible requirement if all lights had been on for the same period of time. The fact that the full lighting capacity is rarely used indicates that the system may be oversized, however the system was designed to be able to provide 350 lux in the offices in the absence of any daylight contribution.

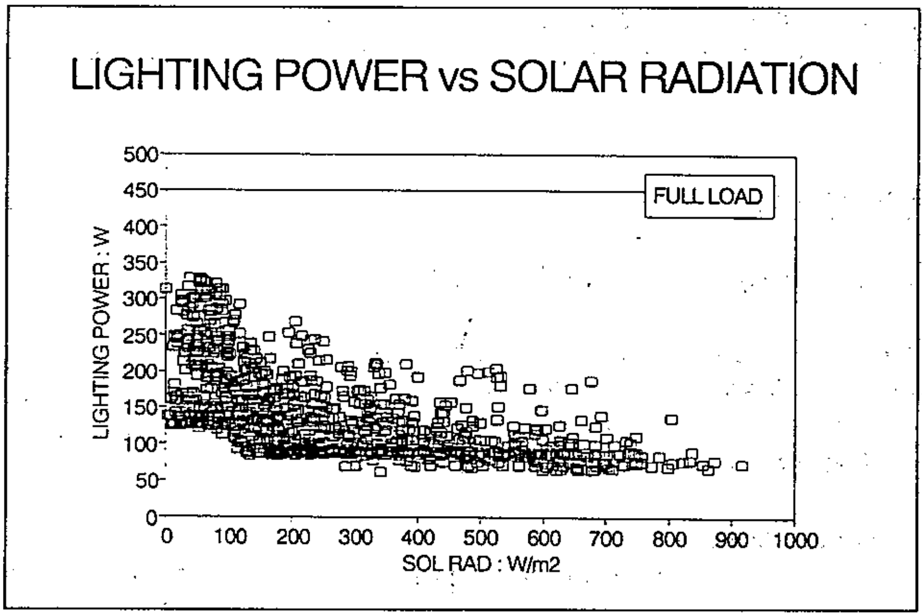


Fig 13

DPEM PREDICTION

The DPEM has used 4 weeks of measured data to adjust the 'Superlite' daylight predictions and lighting control model for the 344m² office facing SE and SW. This allows lighting energy use to be predicted for the whole of the measurement period and figure 14 shows good agreement (ignoring holidays). Figure 15 shows the annual projection of energy use using DPEM for the Kew 1964/5 standard weather year. At 9.3 kWh/m² pa this is less than the observed average of 21 kWh/m² pa for this floor although this latter figure includes the service core and circulation areas (approx. 140m²).

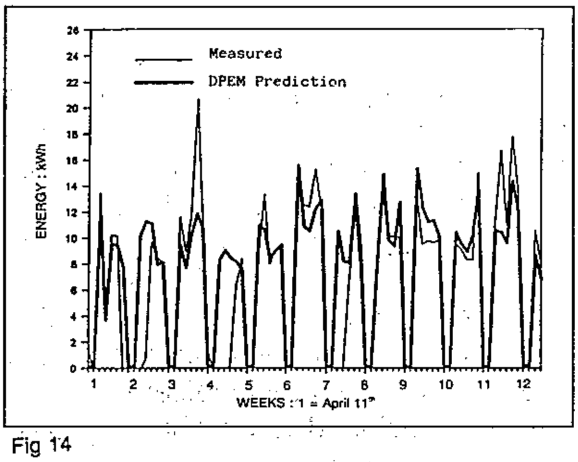


Fig 14

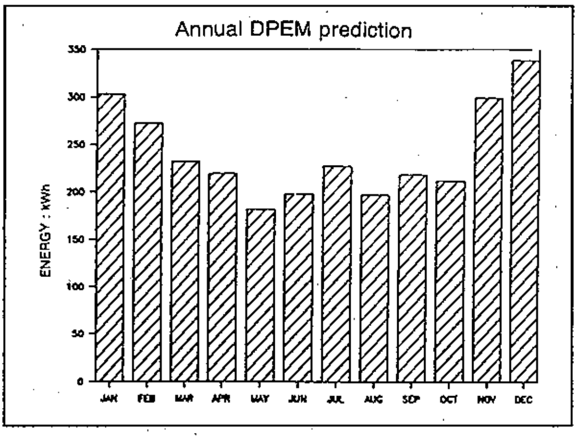


Fig 15

These observations, taken together with the apparent sensitivity of energy use to available daylight suggest that the NW and NE offices may be using significantly more energy, but this awaits further analysis. A simple contribution to the explanation could be that the NW & NE offices have windows in two rather than three walls as in the SE office.

VISUAL APPRAISAL

GENERAL APPEARANCE OF THE INTERIOR

When entering the second floor south east facing office the impression gained is one of a pleasant, well lit space which does not feel particularly 'deep'. The beige, cream and white surfaces are light without appearing too uniform and bland, and they are punctuated effectively by dark edge details.

Reflectance values are :-

floor, beige carpet	17%
walls, cream wallpaper	47%
ceiling, white acoustic tiles	68%

The desks and tables have a medium wood finish with dark brown upholstery, which is carried through to the 1.4m high screens which delineate groups of work places. There are a few desk top computers, and sundry conventional office furniture including 1.7m high light wood finish units against the back wall.

The office functions are clerical, and small group discussions. The overall impression is one of low occupation by people, but with a moderately high proportion of space occupied by furniture, fittings and equipment.

The windows are cleaned every three months and the external shelf every six months. Considering the suburban location together with the cleaning schedule would give an average to good maintenance factor for dirt on windows and interior finishes.

VIEWS AND LUMINANCES

In general views out are of the local park, the main road and nearby factories. Additionally the windows occupy 70% of the window wall width in an almost continuous strip on at least two sides for large offices. The frame occupies a typical 26% of the window aperture, however the depth of the shelves produces an increased obstruction for many angles of view.

Harsh contrasts between the window surrounds and the sky seen through the window can produce glare. The light admitted by windows in adjacent walls, the high reflectances of interior finishes and of the window frame, cill, shelves and soffit to the overhang all considerably reduce the contrast with the sky. The inter-reflections between the shelf underside and cill and of its topside with the ceiling are particularly important.

The external reflectors enhance daylight reflection but their effect is particulary noticeable when for certain sun positions reflections of direct sunlight shine on to the ceiling producing interesting patterns. The vertical blinds over the lower window can exclude sunlight from most working positions, but occasionally low angle sun reaches occupants through the upper window in an adjacent facade and expedient pieces of paper have appeared on the glass to ameliorate this.

NO SKY LINES

Conventional daylight analysis tends to use rooms with a single window frame rather than the more complex configuration in this building. Here there are effectively two windows both with external overhangs and the effect of both is modified by the internal shelf.

One appropriate way of describing the daylight distribution is to show cut-off lines produced by different parts of the window system. Figure 16 shows the obstruction effects on the direct component of daylight by the solar shading. The otherwise large sky component from the high window head (3m) is obscured close to the window, but penetrates to the back of the room. At a 0.7m desk height (fig 17) the direct component received to a depth of 3.5m results from the lower window only and is reduced by shelves. Positions between 3.5m and 6.7m receive an increasing contribution from the upper window which is then totally unobscured beyond 6.7m.

To the eyes of seated occupants these cut off lines are at different room depths. For occupants seated up to 2.5m from the window their eyes will receive less direct daylight from the lower window than that received on the desk tops. This is generally true in side lit interiors, but the difference in this case is that the upper window produces an inverted version of this effect at desk positions beyond 2.5m, where the eyes receive more direct light than the desk. Beyond 4.7m the upper window is completely obscured.

The enhanced illumination of the back wall and consequent inter-reflection from the ceiling help offset the highly directional qualities associated with deep side lit interiors.

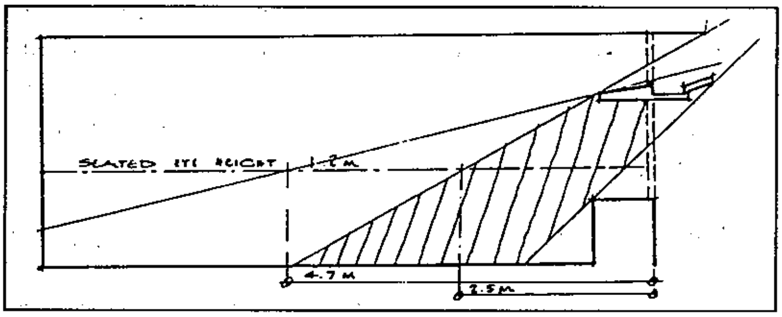


Fig 16 Seated eye height

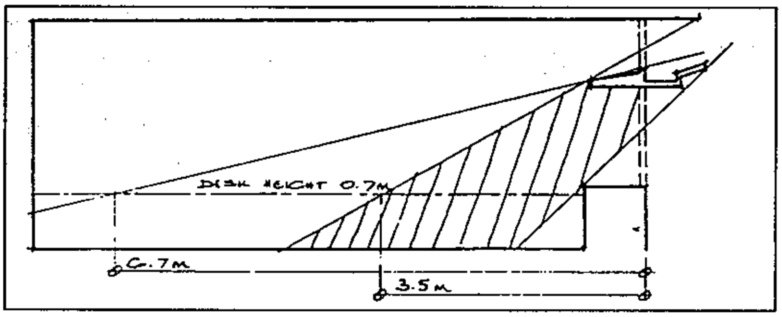


Fig 17 Desk height

DAYLIGHT FACTORS

The first figure overleaf show daylight factors at 0.7m height for overcast sky conditions derived from the datalogging experiments in both SE and NW offices. Sixteen Sundays have been selected for analysis of the daylight within the offices, since on these days all internal light was daylight. Overcast skies were determined from pyranometer readings of total horizontal and diffuse irradiance. It also shows that design predictions from an artificial sky model compare well with measured data.

Figure 17 compares daylight factors at 1.55m and 0.7m heights obtained from the datalogging experiment on two parts of the same overcast day. The figure illustrates the greater obstruction effect of the shelves on sensors nearest to the window.

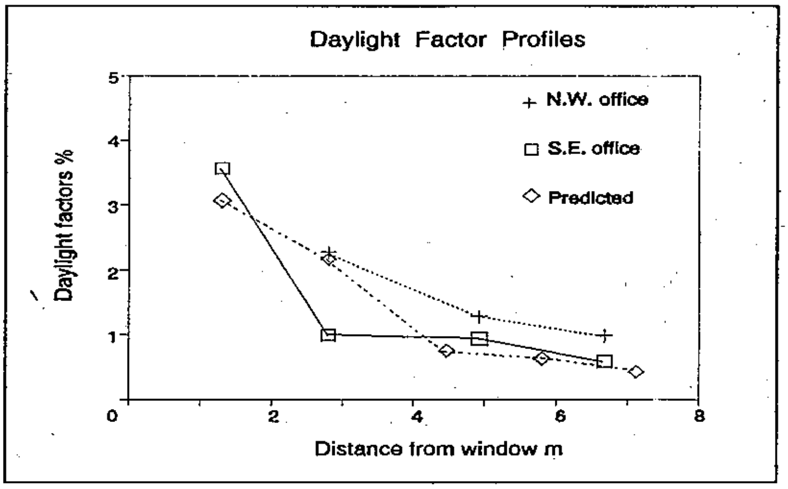


Fig 18

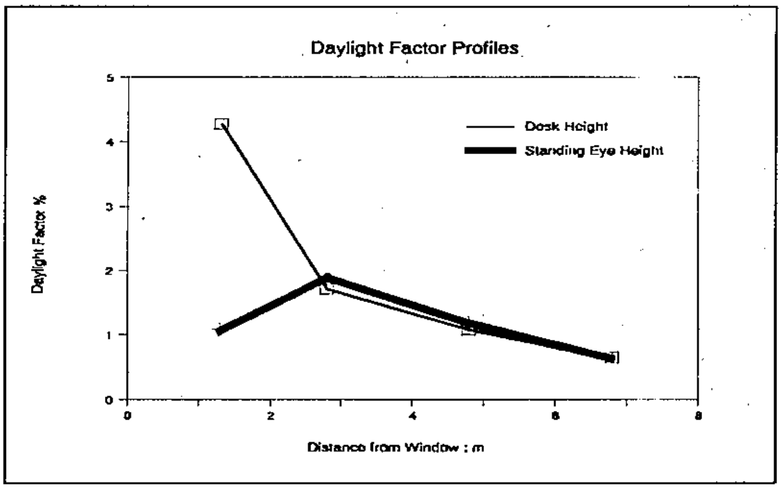


Fig 19

Discussion of daylight factor measurements.

For overcast sky conditions the average daylight factor in the SE office was about 2% and the minimum about 0.7%, giving a uniformity (minimum/average) of 0.35. This is consistent with daylight being the principal source of illumination as stated in the current CIBSE code.

Daylight Redistribution.

The design team use the phrase "redistributed daylight" in describing the building. To assess the degree to which this is effective it is worth clarifying the fundamental mechanisms thought to be acting :-

(i) ADMISSION :-
A large window area allows more admission of light. The higher window head gives both more admission and greater penetration onto the rear wall and desks.

(ii) EXCLUSION :-
The external shelf excludes high sky daylight from the high sky from reaching the front of the room through the lower window. The internal shelf excludes such light from reaching the front of the room through the upper window.

(iii) INVERSION OF LIGHT GRADIENT WITH HEIGHT :-
The duel window ensures that the upper section contributes daylight to the rear rather than the front of the room. This contribution increases with height due to the high effective cill of the upper window. At the front of the room, daylight decreases conventionally with height.

(iv) INTER-REFLECTIONS :-
Because of the greater penetration of light to the rear wall and desks there is more light reflected from these surfaces up to the ceiling, so there is also more inter-reflected light at the back of the room.

These four effects combine in different ways to produce the total daylight distribution. Comparing this dual window with a simple window with 3m head height, effects (ii) and (iii) do not increase daylight levels at desk height at the rear of the room, but rather decrease those at the front of the room. With the contrast in levels between front and rear of the room having been reduced, the rear of the room will **appear** lighter especially at eye heights. Effects (i) and (iv) actually do increase daylight levels at the rear of the room, again particularly at eye heights. Effect (iv) reduces the directionality commonly associated with side lighting in deep rooms.

The overall effect is to produce a daylight distribution with a greater uniformity between front and rear of the room compared with a simple window system. Moreover, it produces an even greater front:rear uniformity at eye heights than at desk height. In particular, the higher level and quality of daylight at eye height at the rear of the room could well affect the users' perceptions of the interior and consequently, their desire for supplementary electric light.

These analysis support the theory that it is more accurate to say that the daylight has been modified rather than redistributed. Redistribution is more apparent than real.

The impact on energy use may be related to the perceived daylight levels which might trigger a desire for electric lighting. The apparent redistribution and increased uniformity (especially at general or eye heights) may combine to produce a lower trigger illuminance at the work plane. Entrance doors and switches are remote from the window wall, so occupants make lighting decisions whilst experiencing these general effects. This is consistent with the observed negligible use of task lighting and the very limited call for overhead lighting.

Electric Lighting and Control

This appraisal is concerned with electric lighting, therefore in order to assess some of the effects of the electric lighting installation it was necessary to visit the interior at night so that the installation could be seen alone.

The overall impression is of generally bright horizontal work surfaces and a rather gloomy ceiling (this could well complement the daytime lighting since the ceiling is rather well daylit). The windows gave a noticeable 'black hole effect' to the external walls. A night time test of the electric lighting levels confirmed this visual appraisal. Whilst the average level of 360 lux accords with design specification, low values (approx 100 lux) near to the window wall and high values (≥ 600 lux) by the wall wash effect lighting, are contributory to a lack of uniformity. The negligible reflectance of the large percentage of glass in the exterior wall results in the low light levels near the windows. This variation in the internal wall reflectances should be accounted for when designing electric lighting installations for rooms with large window areas such as is common in passive solar design. Light coloured blinds or curtains at night would also seem worthwhile recommendations.

ACKNOWLEDGEMENTS

Much of the data used in the preparation of this paper was collected by Databuild under contract to the Energy Technology Support Unit. The views expressed are those of the authors.

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ATRIUM SECTION

NOUVELLE UNIVERSITE DE NEUCHATEL

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Swiss Federal Office for Energy

INTRODUCTION

The new building of the faculty of literature of the University of Neuchâtel, Switzerland, has a heating energy demand of only 291 MJ/m2a (including DHW, see Figure 4). The symmetrical building has a central courtyard and an attached atrium. It is heated by a heat pump with back-up provided on extremely cold days from district heating. The large prominent atrium was conceived as a passive solar-heated space. The building is deliberately not air conditioned and only a limited number of special rooms have mechanical ventilation. The glazed space is cooled in summer through natural ventilation and evaporative cooling from pools of water.

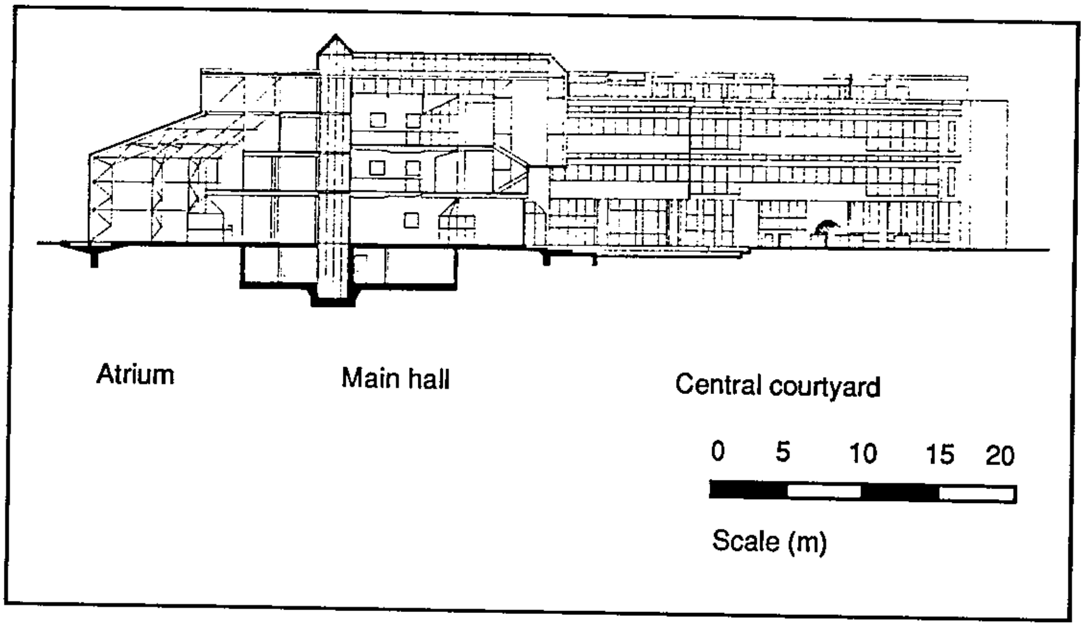


Figure 1: Cross section of the building

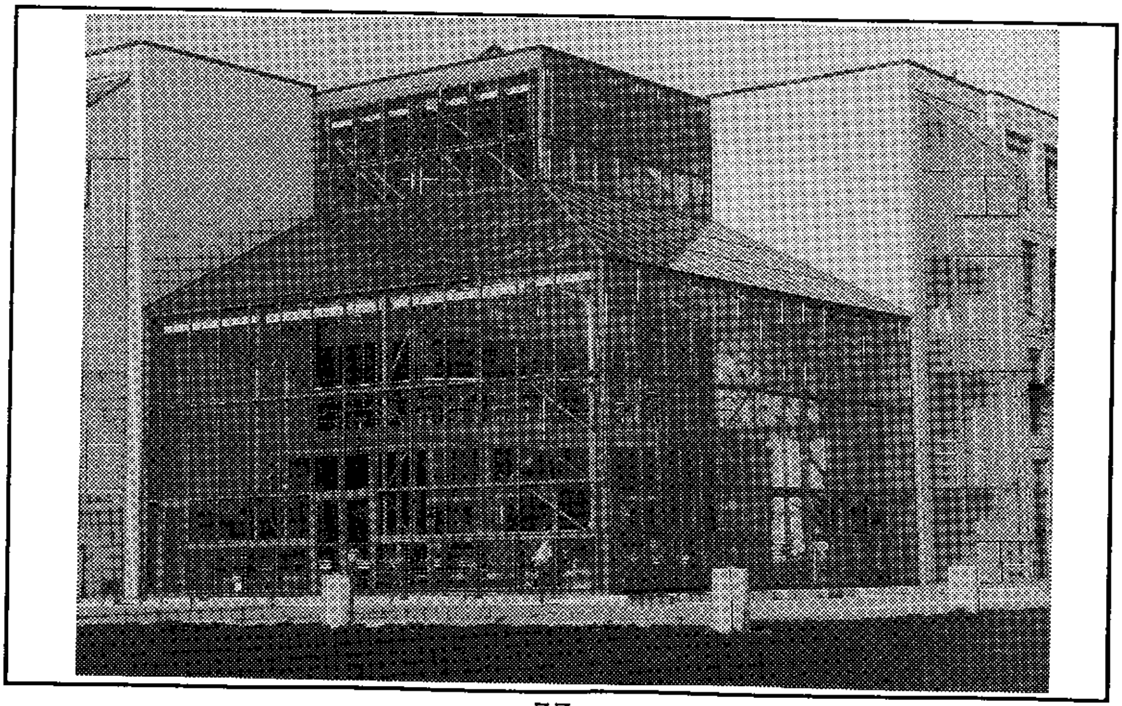


Figure 2 : Atrium without shading device

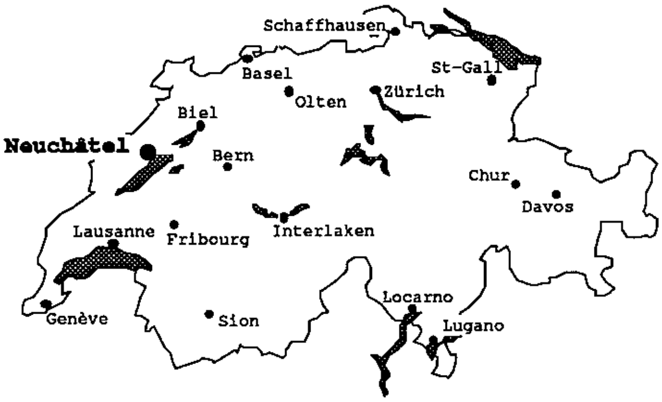
PROJECT DESCRIPTION

This particular building design was chosen from among the entries to a design competition. The energy consultant, who was engaged in the project from its inception, gave particular attention to the atrium.

During the course of 1989 the project was monitored in detail within the framework of the Swiss participation in IEA Solar Task XI. The chief goal was to assess the level of comfort in the atrium under different climatic conditions during winter and spring.

To achieve this objectives, the thermal behavior of the attached atrium, was studied and quantified, utilization (comfort), analysed and then compared with its actual utilization, and protection against overheating (sun shading and natural ventilation) evaluated. Temperature stratification and air movement were also studied.

By means of computer simulation the parameters of glazing, size of ventilation openings, placement of sunshading and orientation were analyzed.



Geographical data	
Latitude	47°00'N
Longitude	6°57'E
Altitude	438 m

Climatical data	
Global horizontal radiation	1191 kWh/m^2 yr
Heating period duration	215 days/yr
Degree-days (20/12°C)	3413 DD/yr

Figure 3 : Situation

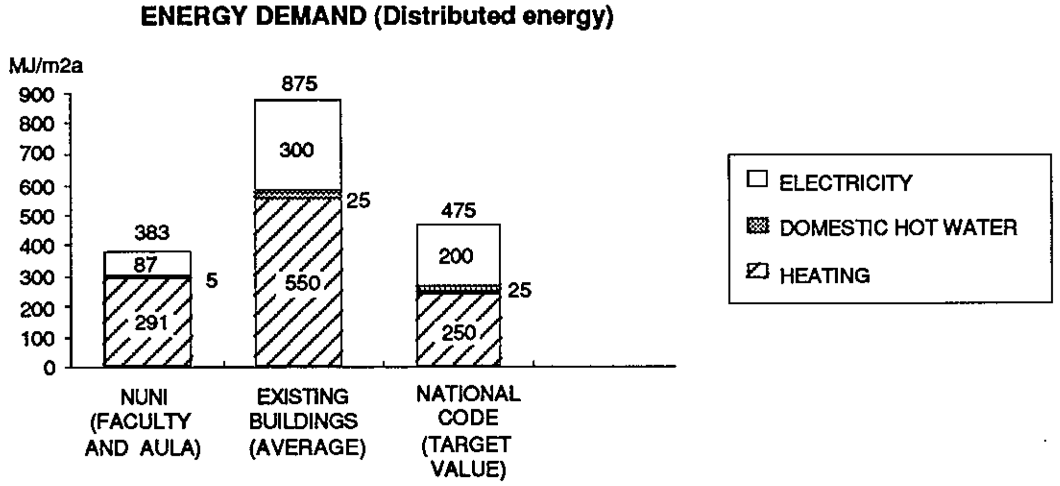


Figure 4: Energy demand

SITE AND LOCATION

The project is located on a landfill site on the Lake Neuchâtel.(see Figure 3) To the west is a large open park area.

BUILDING FORM

The 3-4 story building complex, organized around a central court, comprises six blocks:

- four almost identical blocks housing a library, class rooms and offices
- a 12 x 12 x 12 m atrium with 160 m2 of vertical glass and 130 m2 of inclined glass.
- a central block with the entry hall, cafeteria and common area.

A pedestrian axis passing diagonally through the building connects the town to the open park land foreseen for festivals. This axis passes through the common area, which can be used independently of the remaining building activities.

BUILDING CONSTRUCTION

The concrete framing, ductwork and other services are all exposed rather than being hidden with a suspended ceiling. The construction is based on a 7.2 m grid. The atrium is single glazed on the outside as well as on the connecting wall to the main building.

BUILDING SERVICES

80 % of the heating requirement of the building is covered by the two heat pumps, each with 500 kW capacity. One of these uses a nearby sewage treatment facility as a heat source, the other uses heat rejected from an artificially-cooled ice skating rink. The heat-pumps are adequate to heat the building when outdoor temperatures are above -15°C. Below this temperature, district heating is also used. Excess heat produced by the heatpumps during mild weather is fed back into the district heating. Heat is delivered to the rooms via floor heating. The principle spaces are heated to 20°C, the common areas and connecting spaces are heated to 16°C. A ventilation system is provided for the common areas, the auditorium and the library stacks .

PASSIVE SYSTEM

The atrium is divided in two zones, an outer zone that is unheated and serves as a solar tempered buffer, and an inner zone that is heated. In the summer large glazed areas (6 % of the total atrium glass area) can be opened at the base and top of the atrium (11 m height) to induce natural convection. Pools of water at the perimeter further enhance natural cooling by evaporation. Interior sun-shading provides glare and overheat protection.

COSTS

The entire building complex was estimated to cost SFr. 17,500,000. Actual costs were 20 percent higher. Part of this additional cost included supplementary insulation, which it was decided to install during the course of construction.

ENERGY PERFORMANCE

The estimated annual energy consumption for heating is 290 MJ/m^2a (see Figure 4).

HUMAN FACTORS

The fact that the atrium is frequently occupied and is indeed often filled to capacity underlines its success as an informal gathering area. Students are apparently willing to accept the cooler temperatures of the space in the winter in order to enjoy the amenity of its "outdoor" character.

MEASUREMENTS

The measurements performed from mid February 89 to the end of June 89 enabled some major questions about big attached atriums to be answered, for example the following :

- horizontal and vertical stratification effects
- passive cooling device efficiency (sun shading, natural ventilation)
- potential utilization versus actual utilization (comfort)

The main observations may be observed as follows:

There is no horizontal stratification in the atrium.

Concerning vertical stratification (see Figure 5), a typical series of three days having similar meteorological conditions allowed some essential caracteristics of the atrium to be demonstrated.

On the first day (27th of March), there is no shading, and the natural ventilation openings are closed. The indoor temperature reaches 47 °C, and the stratification is weak.

On the second day (28th of March), the shading devices are used and the natural ventilation vents are open. In this case the indoor temperature remains below 30 °C, and the temperature drop between the top and the bottom is about 10 °C.

On the third day (29th of March), the natural ventilation openings are closed, and the shading devices are in the low position. In this case, the indoor temperature reaches 35 °C at the bottom of the atrium.

The analysis of these three days shows that whenever the shading devices are not in the low position, the solar energy mainly heats the lower part of the atrium, creating convective air movements that destroy the stratification. However, when the shading devices are in the low position, the solar energy entering the sun space heats the shading device over the whole height of the atrium, and there is no convective air movement. The stratification is very marked (about 20 °C) between top and the bottom of the atrium (12m height).

A comparison of potential and actual atrium utilization is given in Figures 7 and 8. These show classified PMV duration measured and the actual atrium utilization time during the months of March and June.

It can be seen that in March (Figure 7), the atrium is under used, whereas it is very well frequented in June.

The problem of utilization of the shading devices has been investigated (Figure 8). For the same period as before (March and June), it can be seen that the shading devices are not employed sufficiently to protect against overheating in mid-season, and that once they have been brought to the low position, they remain in this position even if the PMV has come down to 0.

Based on these observations, it is recommended that a temperature sensor be placed in the atrium and the reading displayed inside the building. For the most part, as soon as the atrium indoor temperature reaches 15 °C, the level of comfort is sufficient. By this simple means, users could be made aware of the fact that the atrium is warm enough for use.

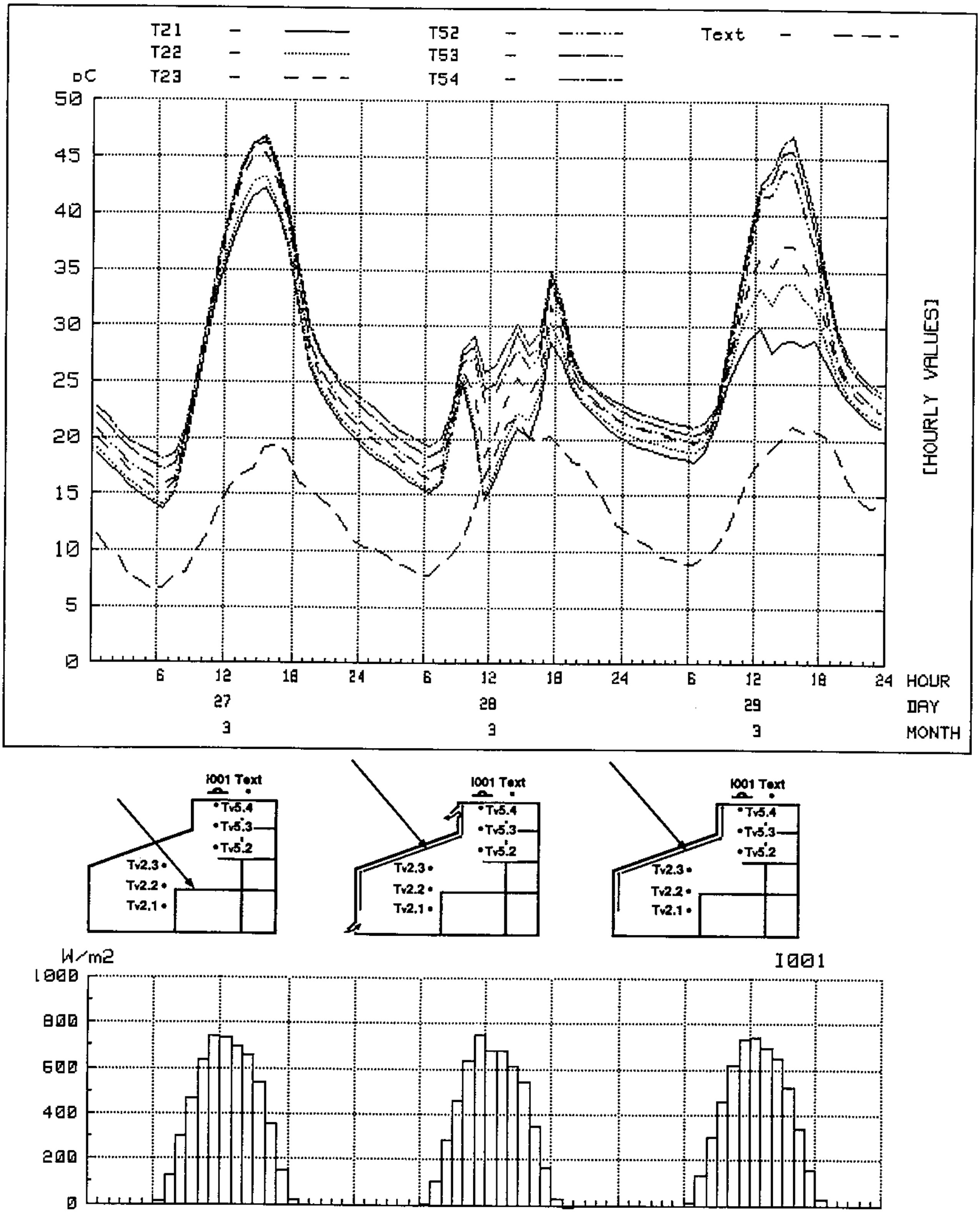


Figure 5: Measurement (March 89): Vertical temperature evolution in the atrium

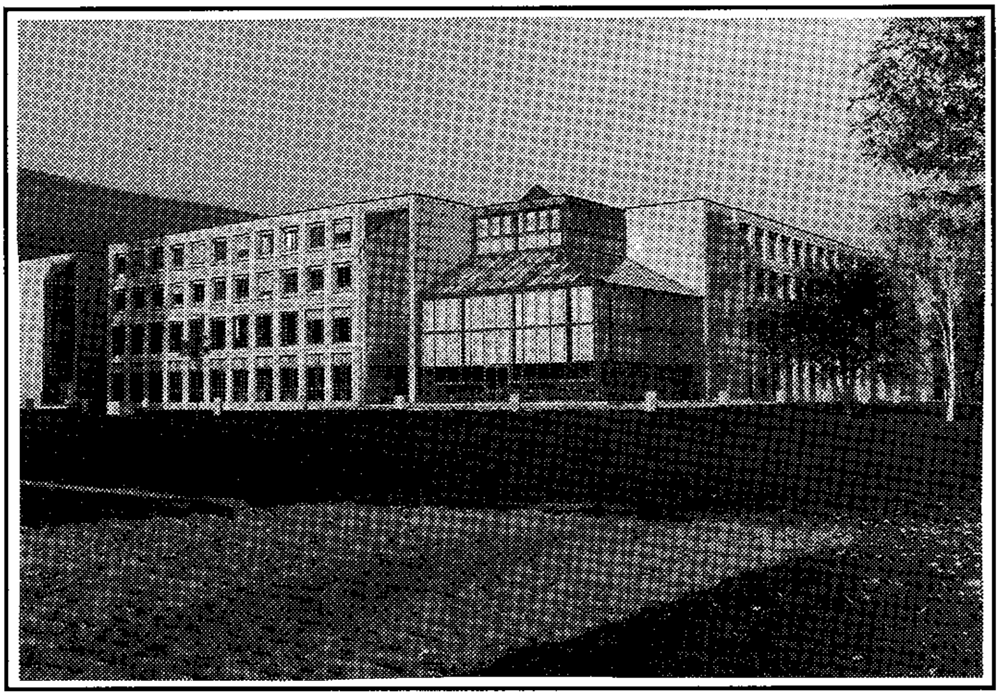
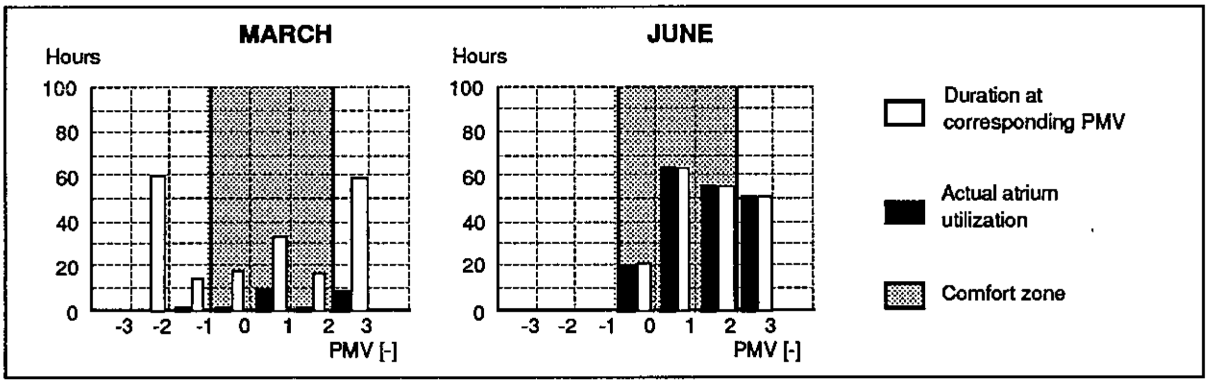


Figure 6: Atrium with shading devices and building (seen from South)



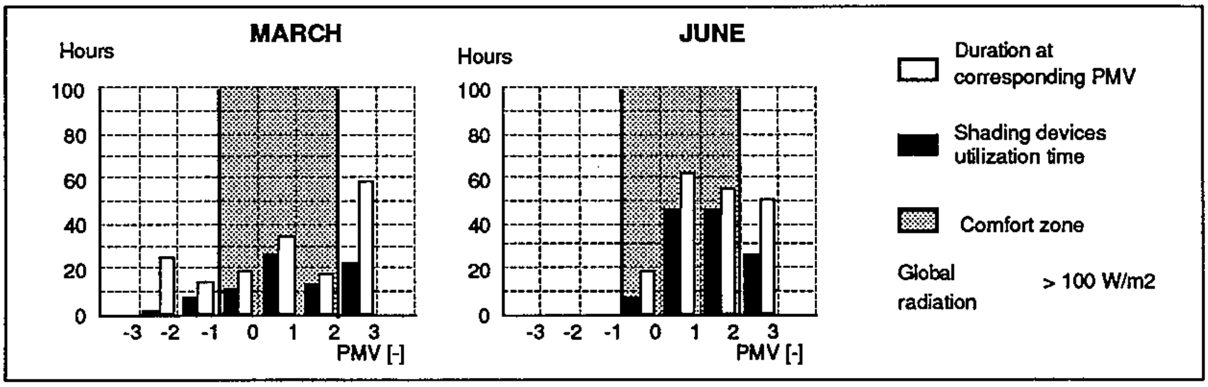


Figure 7 and 8: PMV duration and use of shading

SIMULATION

The atrium was modelled with the MODPAS program. The atrium was discretized using 40 nodes linked together. The code was validated on the basis of temperature.

LESSONS LEARNED

The main problem encountered was related to the solar radiation distribution between the different nodes. The initial distribution had to be modified in order to take into account the effects of furniture and the steel structure. The comparison between measured and simulated temperature distribution showed good agreement.

PARAMETRIC ANALYSIS

The parametric study focused on the heating period. Its main goal was to evaluate the impact of different parameters (glazing, orientation, inertia, heating) on energy and comfort aspects.

The level of comfort was computed on the basis of a multiple regression between the measured PMV and the internal air temperature, the glazing temperature and the indoor transmitted solar radiation.

MAIN RESULTS

For the climate of Neuchâtel, four configurations with different conditions where studied :

- no atrium, facade with double glazing (NFD)
- atrium with single glazing, facade with single glazing (ASFS)
- atrium with double glazing, facade with single glazing (ADFS)
- atrium with single glazing, facade with double glazing (ASFD)

The results are summarized in Figure 9.

The reference 0 for absolute energy saving is the NFD. For relative energy saving values, the reference 100 % is the ASFS, and the reference 0 % is the NFD.

The results show that, in comparison to the reference case, the energy saving achieved by the non-heated atrium varies between 5 and 17 MWh/a. On the other hand, when the atrium is heated, the surplus energy consumption varies between 19 and 107 MWh/year. It is therefore clear that heating an atrium to a temperature level that keeps a high level of comfort over most of the time is very energy intensive.

Comfortable conditions occur during about 25 to 40 % of working hours (8 to 17 hours) for non-heated atriums, and between 80 and 95 % for heated atriums. The corresponding figure for outdoor conditions is less than 5 %.

It is important to note that the energy consumption is highly influenced by the thermal quality of the atrium (or facade). On the other hand, comfort is improved only slightly by substituting double glazing for single glazing on the atrium.

The results obtained for five IEA climates are shown in Figure 10.

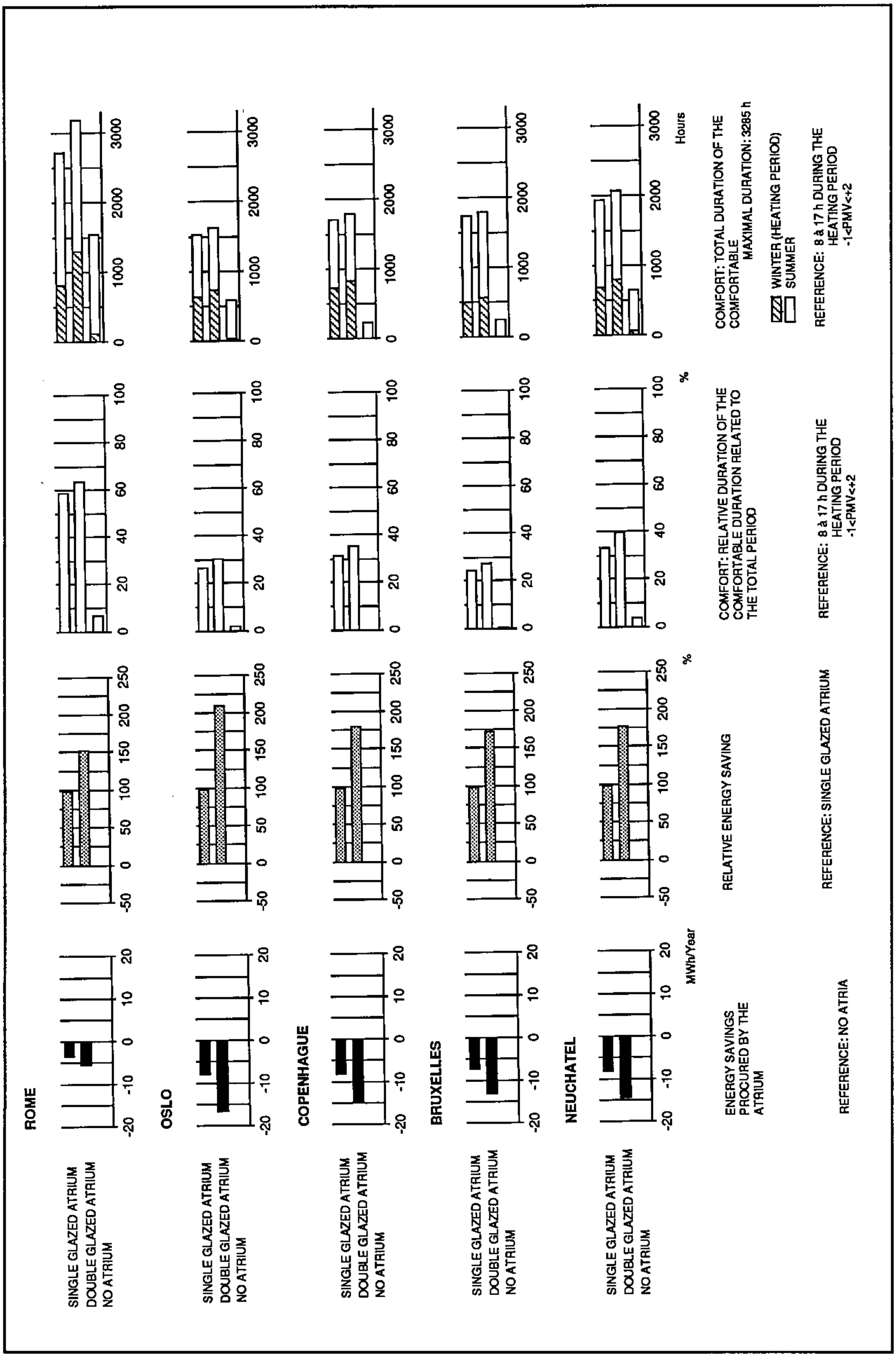


Figure 9: Parametric analysis

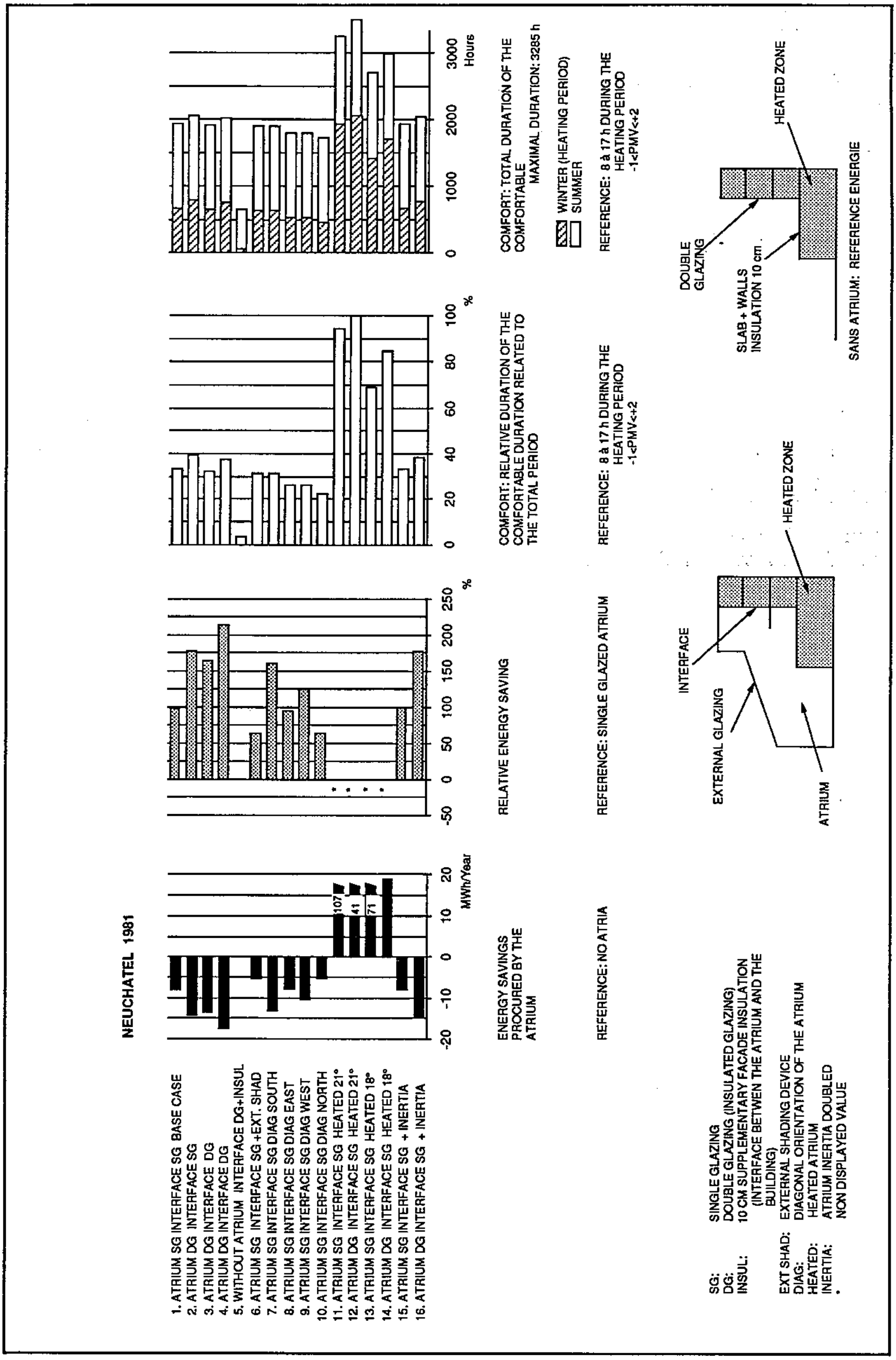


Figure 10 : NUNI atrium under different climatic conditions

CONCLUSIONS

The results of the project show that comfortable conditions in non-heated atria occur during 25 to 40 % of working hours over the heating period. The energy saving obtained in comparison to no atrium ranges between 5 and 17 MWh/a. If comfortable conditions with indoor temperatures at 20 °C are desired, heating requirements are exhorbitant. The supplementary energy required for the heating of a NUNI atrium ranges between 19 to 107 MWh/a, depending on the conditions (Figure 10). The passive cooling system (shading and natural ventilation) is adequate for summer.

INFORMATION

The information for this report is from J.-M. Triponez, NCL Architecture Urbanisme, CH-2300 La Chaux-de-Fonds and from D. Chuard, Sorane SA, Route du Châtelard 52, CH-1018 Lausanne.

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THE PI-GROUP HEAD OFFICE

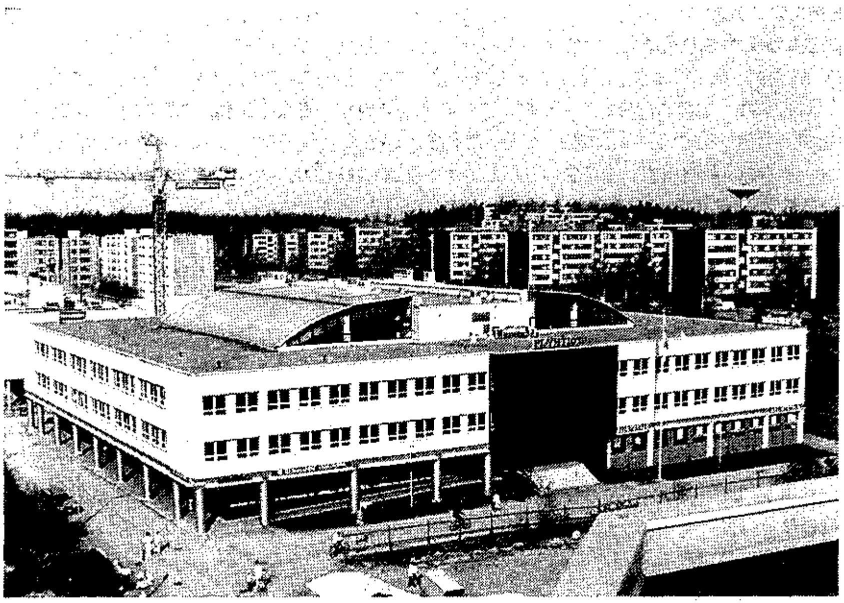


Figure 1. The External View of the Building

ABSTRACT

This paper presents a case study approach to the investigation of the thermal performance of two glazed atria and their open lightwell alternatives in an office building in Finland.

The case study building has two storys of office space, which are daylighted through two central atria in the interior zone. Both of the atria are glazed in order to reduce the heat loss of the external envelope of the building and increase the occupancy potential of the central courtyards. The energy performance of the glazed atria, together with the effect of glazing on the energy use of the building, is evaluated by a thermal simulation model. In addition, the thermal behavior of the glazed atria as well as the energy performance of the building is evaluated by long-term measurements.

The study shows an advantage of heat loss savings of 15 % and 17 % for the glazed atria over the corresponding open lightwell envelopes during the heating season, when the glazed atria are heated up to 17 °C and the target temperature in the adjacent office space is 22 °C. It also shows a disadvantage of heat gain increase of 5 % and 7 % for the glazed atria over the open lightwell envelopes during the cooling season, when the glazed atria are naturally ventilated and the target temperature in the adjacent office space is 25 °C.

INTRODUCTION

The code of building regulations in Finland sets requirements for daylighting of working spaces. Lightwells have been architectural solutions for daylighting of the interior of deep plan buildings. New building technologies and materials, together with concers over energy efficiency of buildings, have developed the idea of glazing of the lightwells in order to reduce the heat loss of lightwell envolopes and increase the occupancy potential of courtyards.

The design trend of atrium building has been growing rapidly during 1980s in the Nordic countries. Many of existing lightwells and open courtyards are converted or are being considered for conversion into atria. The growing trend has activated many national and international research projects and case studies of atrium buildings.

The aim of this case study was to evaluate the thermal performance of two central atria (glazed lightwells) in an office building in Finland. The energy performance of the atria is evaluated and compared with the heat loss and heat gain effects of the corresponding open lightwell envelopes on the adjacent office space by a thermal simulation model. In addition, the thermal behavior of the atria as well as the energy performance of the whole building are evaluated by long-term measurements. The simulation results are validated and enhanced by measured data.

THE CASE STUDY BUILDING

Site and Location

The building is located on a flat site in a tight commercial center of 3 to 7 level buildings of the city of Vantaa, which is about 15 km northwest of Helsinki. The location and monthly averages of global irradiation on horizontal and external temperature are shown in Figure 2.

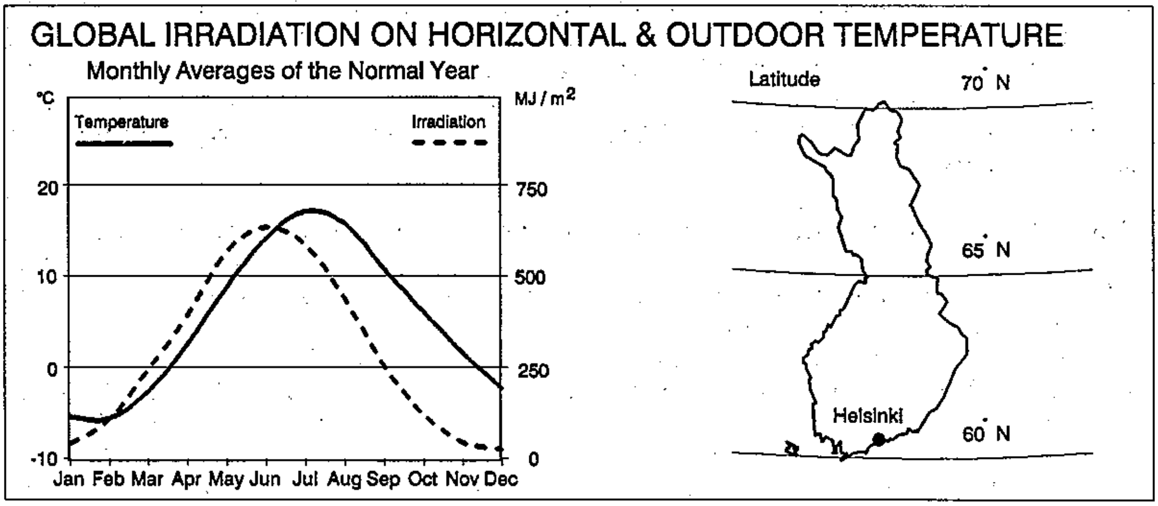


Figure 2. Site Location and Climate Data

Building Forma and Applications

It is a 3-story cubic building, 60.8 m long, 53.6 m wide, and 11.4 m high with a total gross volume of 39,100 m^3. Two atria of 366 m^2 each are located symmetrically in two centers of the building. One of the atria is on the ground floor level with a height of 13 m and a volume ration (atrium/total) of 0.12. This atrium has a south-facing skylight (SFA) and it functions as a transitory to the outside. The other atrium is on the first level with a height of 9 m and a volume ratio of 0.09. Its skylight is facing north (NFA) and it is used for internal circulation. Two storys of office space are wrapped around the atria. The atria are used as plant rooms and they provide daylight to the adjacent offices. The ground floor of the building is used for public and commercial services. The basement of the building is used for shelters, storage, hobby and social spaces, and technical rooms. The attic space on the third level between two atria is an executive space with a conference room, dining room, kitchen, services, and two saunas. Building section and plan are shown in Figure 3.

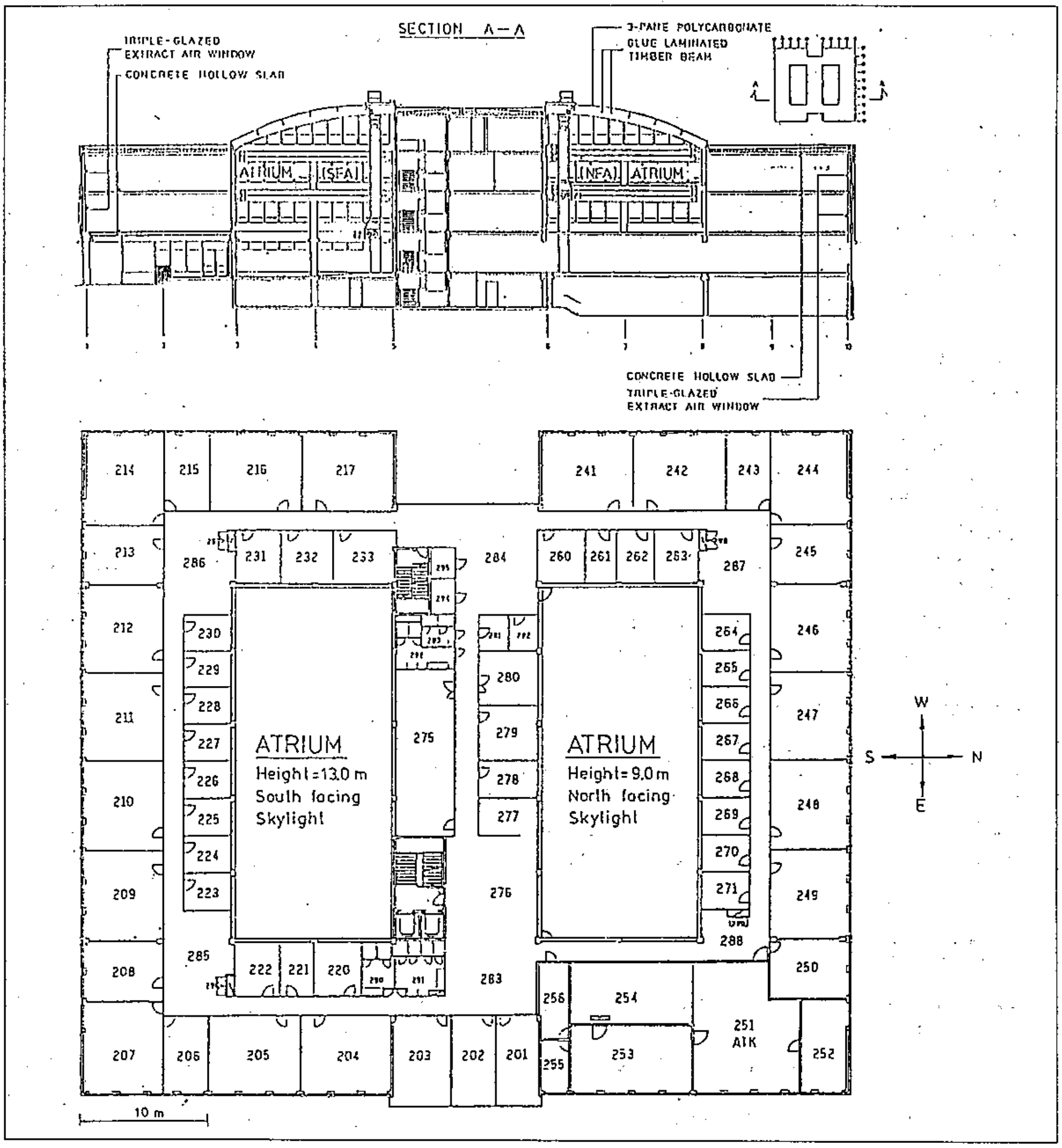


Figure 3. Section of the Building and the Floor Plan of the Office Space

Construction

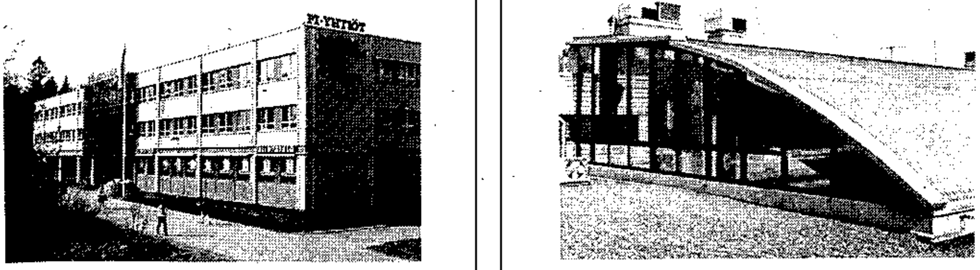
The building has a reinforced concrete frame with facing brick finish. The exterior walls in the perimeter zone of the building include 140 mm mineral wool and the windows are triple-glazed extract-air windows in offices. Elsewhere they are normal triple-glazed windows. The intermediate boundaries of atria are uninsulated brick walls with single-glazed windows. The skylights (glazed roof) of atria, 400 m^2 each, are made of three-pane translucent polycarbonite panels, 60 mm x 88 mm of 6 m long with an average inclination of 17° from horizontal. The vertical parts of the external envelope on the top of the atria facing east and west are glazed by clear triple-glazed window elements, some of which function as automatic air gates for natural ventilation in summertime. Others are designed for fire safety and smoke management, which are controlled automatically by fire and smoke indicators. The floor slabs are hollow concrete and they are used for ducting of supply and extract air of the offices. See building views and close ups in Figure 4.

Heating, Cooling and Ventilating

The building is connected to a district heating network. The air-conditioning system of the offices has two zones. One serves the south and west facades and adjacent spaces to the atria and is equipped with both cooling and heating capabilities. The other zone, which serves the north and east facades, is equipped with heating capabilities only. In addition, there are split air-conditioning units in the computer suite, the text editing unit, and the copying unit. The attic space between the atria as well as the spaces for commercial services on the ground floor are equipped with separate air-conditioning units. The atria are heated by separate air-handling units and temperature in the atria is controlled by each one's thermostat. In the summertime the atria are naturally ventilated by openings which are controlled by the thermostat of each atrium. During this period, the air-handling units in the atria are stopped in order to enlarge the thermal stratification and optimize the efficiency of the natural ventilation. The temperature control strategy of the atria is shown in Figure 5. A liquid circulation system using an ethylene glycol and water mixture is used as an extract-air heat recovery unit. In addition the excess heat from the refrigeration systems of the commercial spaces as well as the condensing heat of the cooling units are used for space heating.

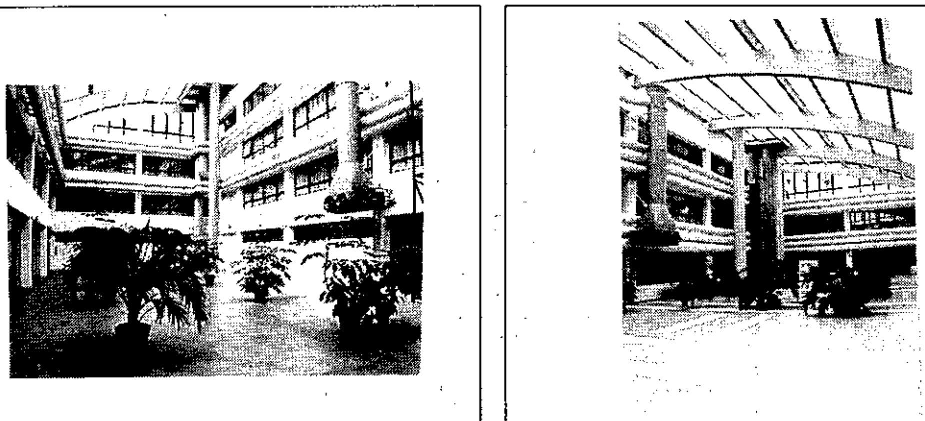
Lighting

The atria provide daylight in the adjacent spaces and windows provide daylight in the perimeter zone. In addition, an indirect lighting system which uses 150 W metal halide lamps was chosen for high color rendition, high efficiency, and long lifetime. Lights are controlled manually.



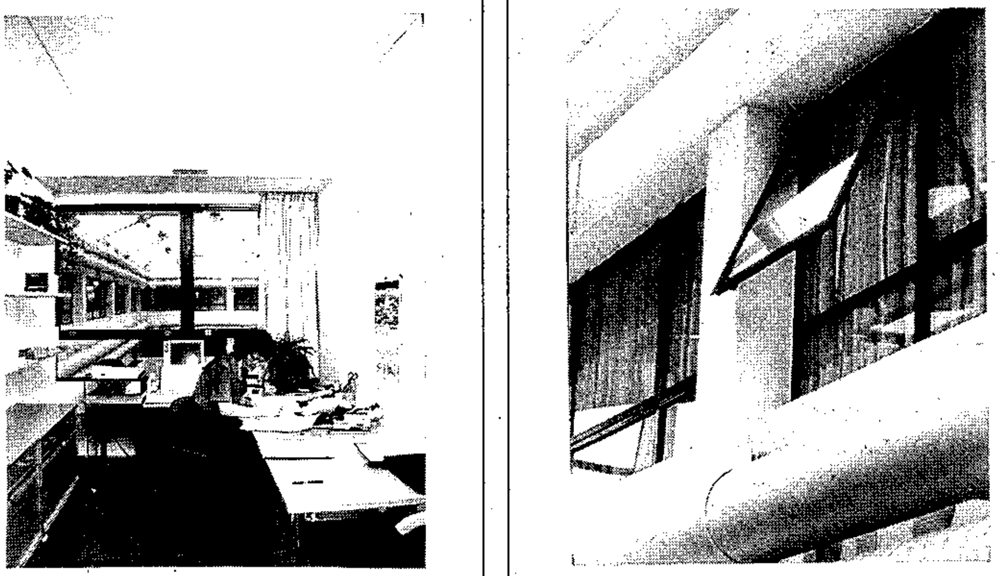
External View to East and North

Atrium Skylight and Air Gates



South Facing Atrium (SFA)

North Facing Atrium (NFA)



An Adjacent Office Facing the Atrium (SFA)

Single-glazed Window of an Adjacent Space

Figure 4. Building Views and Close Ups

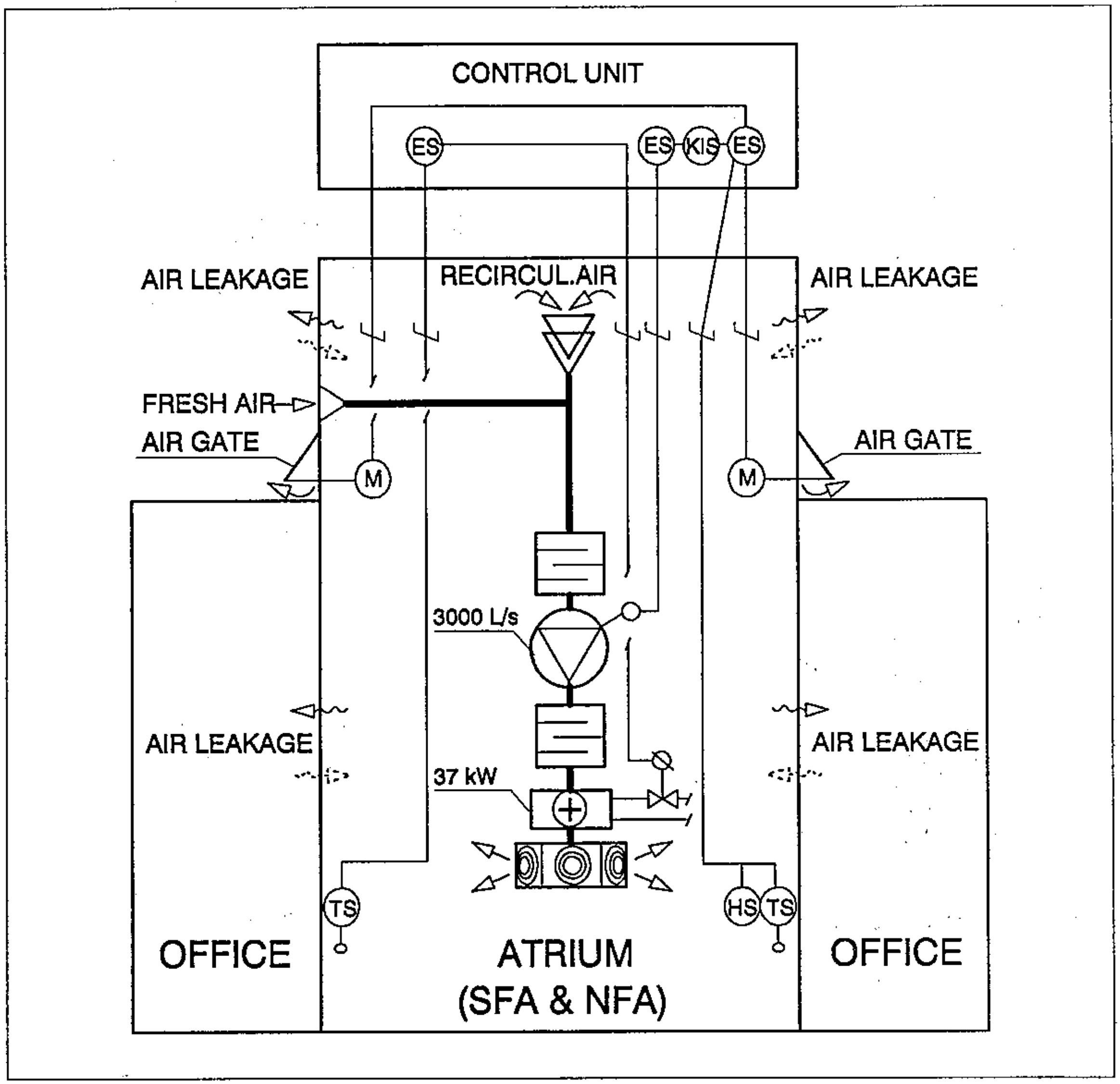


Figure 5. Heating, Ventilating and Temperature Control in the Atria

EVALUATION METHODS

The aim of this study was to evaluate the thermal behavior of the atria and their energy-saving potential as well as the amenity values and building cost. Thermal behavior of the atria is evaluated by monitoring the building and long-term measurements.

A thermal simulation model is used for evaluation of energy-use and energy-saving potential of the atria in comparison to the heat loss and heat gain of the corresponding open lightwell envelopes as the references. The construction of the envelopes of the alternative open lightwells is assumed to be the same as the exterior wall construction of the building with triple-glazed windows.

The amenity values are evaluated by interviewing the building users and owners. Building cost is evaluated due to the actual construction contracts.

Monitoring of the Building

The monitoring of the building was planned in the early stages of the construction project in order to ensure the required instrumentation level. The aim of monitoring was to provide measured data for evaluation of the thermal performance of the atria and the energy performance of the whole building as well as the required data for evaluation and validation of the simulation model. Monitoring of the atria was planned for measurements of the following:

- -- thermal stratification in each atrium
- -- surface temperatures in each atrium
- -- supply air temperature in each atrium
- -- heating power demand of each atrium
- -- heating energy use of each atrium
- -- global solar radiation penetrating the skylight in each atrium
- -- lobal solar radiation outside (horizontal)
- -- outdoor temperature
- -- air change and infiltration rates in each atrium.

A date acquisition system (DAS) was used for the above-mentioned measurements with a record interval of 5 minutes. Thermoelements (T-type) were used for temperature measurements. The sensors were protected against radiation. Air change and infiltration rates were measured by rate of decay method with a record interval of 60 seconds. The accuracy of the temperature sensors was 0.1 °C, the same as for the DAS. The accuracy of the instrument for measurement of the tracer gas concentration was 0.1 ppm. The measured data were transmitted to a microcomputer for further analysis. In addition the whole building was monitored for measurements of the following:

- -- supplied district heat to the building
- -- energy used for space heating (separately for different units)
- -- energy used for domestic hot water (separately for different spaces)
- -- supplied electricity to the building
- -- electricity used in different spaces
- -- electricity used for lighting (office space).

These data were registered from the instrument indicators manually with an interval of one week (in some cases one day) and analyzed by a microcomputer.

Thermal Simulation of the Atria

The Model. Evaluation of the thermal performance of the atria was carried out by a thermal simulation model. The model was developed (Hejazi-Hashemi 1987) based on the transfer function method using precalculated weighting factors (PWF). It is a single-zone model (one-temperature zone) for hour-by-hour calculations. Heat flows of external envelope (walls and fenestration) are calculated by iteration.

Optical properties of the fenestration and external sun shading are calculated due to the sun position at each hour.

Infiltration rate is calculated due to the stack and wind effects based on ambient factors and construction looseness as well as unbalancement of the mechanical ventilation. Air change rate between the enclosed space of the atrium and the adjacent space is given as input data (measured data). Load components are calculated separately using transfer function coefficients (PWF). Space temperature is calculated by iteration method.

The Cases. The objective of the thermal simulation is to evaluate the effects of glazing of open lightwells on the heat loss and heat gain of lightwell envelopes under the circumstances of the case study building. The simulated cases are:

-- two atria (glazed lightwells) of the case study building
-- the same atria assumed to be uncovered (open lightwells).

The simulated atria are heated up to 17 °C during the heating season, when the target temperatue in the adjacent spaces is 22 °C. The extract heat from the adjacent spaces to the atria is calculated due to the transient heat flows and the air change rate (measured data) between the enclosed spaces of atria and the adjacent spaces. The air change rates between the spaces are estimated to be 0.1 changes per hour during the working hours and 0.2 changes per hour at the rest of the time. The extract heat of adjacent spaces together with the heating energy used by the heating coils (air-handling units) of the atria are considered as the heating energy use of the atria. The extract heat from the atria to the adjacent spaces during the heating periods when the atria function as heat sources (early spring and fall) is subtracted from the sum of the heating energy use of the atria.

During the cooling season the simulated atria are naturally ventilated by openings which are controlled by thermostats, but not cooled. During this period the heat gains of the adjacent spaces through the atria are considered as cooling energy loss of the atria. The target temperature in the adjacent spaces is assumed to be 25 °C during this period.

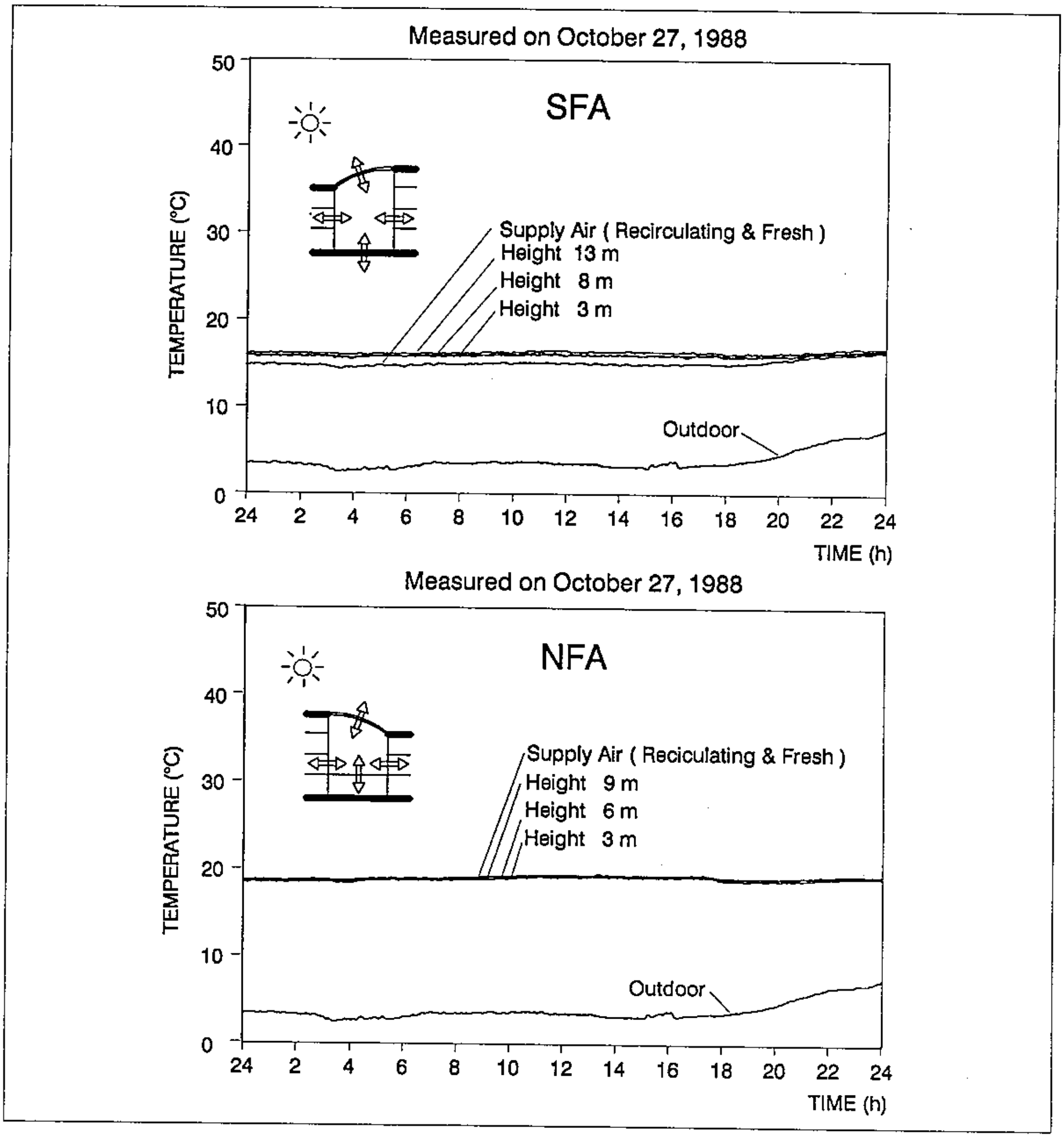
The corresponding open lightwells with standard insulated exterior walls and triple-glazed windows are simulated due to the same adjacent space conditions as the atria. The heat loss and gain of the lightwell envelopes are considered as the heating and cooling energy loss of the lightwell, which are comparable to the heating energy use and cooling energy loss of the atria (effects on the adjacent spaces).

EVALUATION RESULTS

The most significant evaluation results are presented in this section. The evaluation results of two atria (SFA and NFA) are reduced to only one of them when they are indicating similar patterns.

Monitoring Results

Atrium Temperature. Temperature measurement results show that the atria warm up mainly by the extract heat from the adjacent spaces and solar heat gains. The temperature difference between the unheated atria and outdoor varies between 11 °C and 14 °C during a long heating season. This is seen in Figure 6, which shows the temperatures in three different heights of the atrium with a south-facing skylight (SFA) together with outdoor and supply air temperatures in a typical day of this period. The supply air (recirculating and fresh air) temperature is slightly lower than atrium temperature because it consits of 9 % unheated outdoor air. At the same time the atrium with a north-facing skylight (NFA) warms up even more (see Figure 7), as the supply air in this atrium consists much less fresh air rate (1 %).


Measured on October 27, 1988

Measured on October 27, 1988

Figure 6 & 7. Temperature in the different levels of the Unheated SFA & NFA

The temperature control in the atria during the heating period is based on a simple on/off system which starts heating of the atrium supply air (circulating hot water in the coil of the air-handling units) as the temperature in the occupation zone drops below the thermostat setpoint. Correspondingly the heating is stopped (coil is not heated, but the fan runs) as the atrium temperature rises over the setpoint. This is shown in Figure 8, which illustrates the instability (saw-tooth) of atrium temperature.

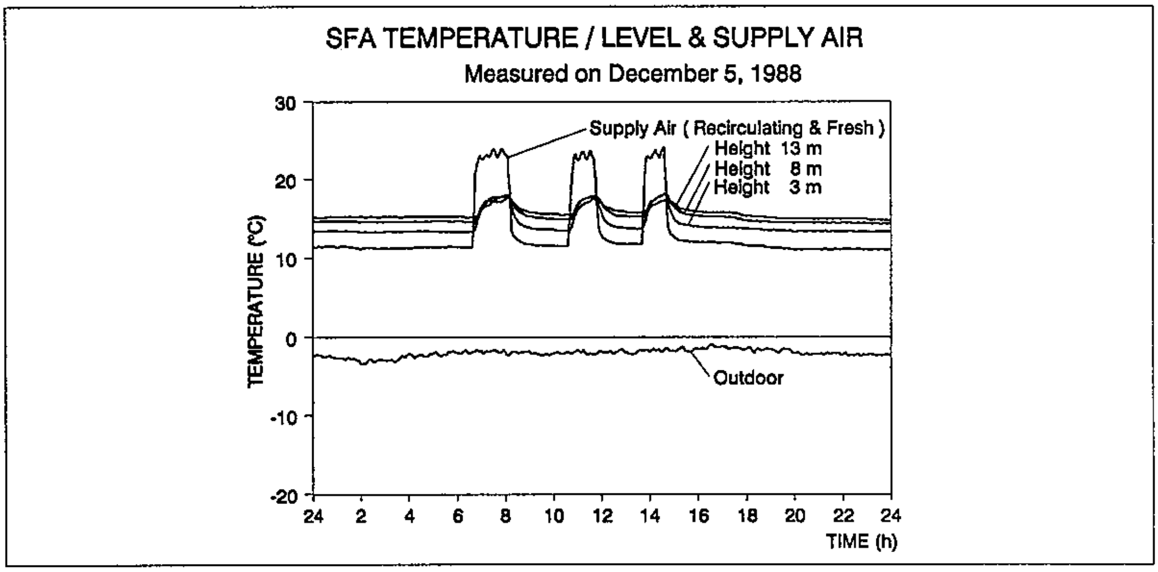


Figure 8. The Instability of Atrium Temperature in the Heating Period, Due to the ON/OFF Control of Heating

Summertime temperature measurements show a high degree of thermal stractification, when the air-handling units are stopped and the atria are naturally ventilated (see Figure 9). The temperature gradient is very nonlinear and two zones of warm and extreme warm are separable.

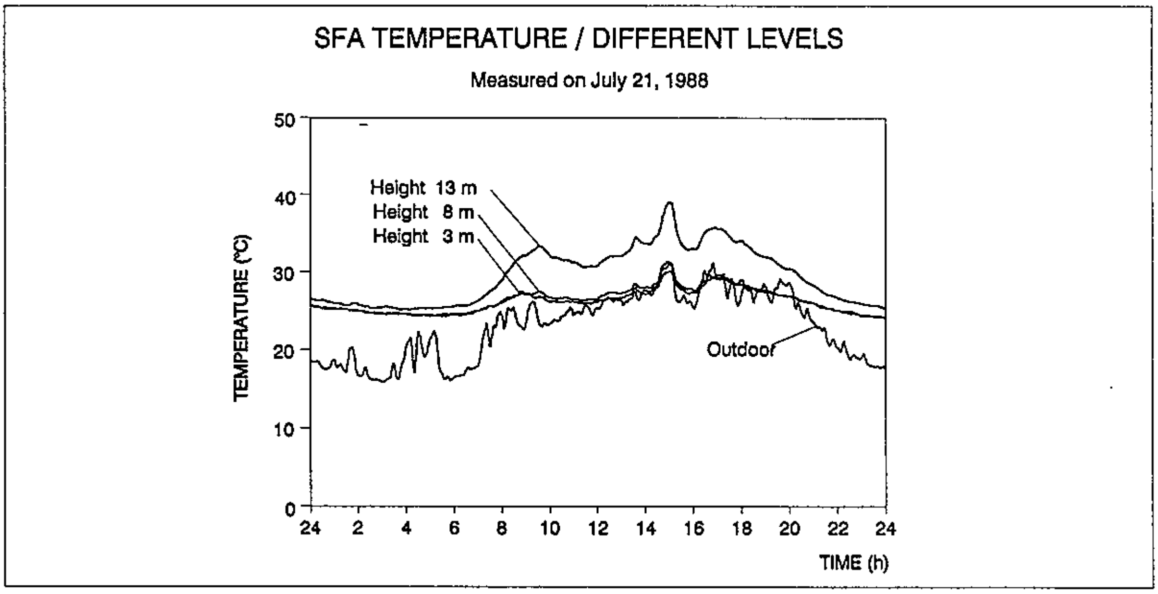


Figure 9. Thermal Stratification in the Naturally Ventilated Atrium

Heating Power Demand. The measurements of hourly demand in heating power of the atria show the effect of solar heat gains on atria heating. The atrium with a south-facing skylight operates as a passive solar collector. This hourly demand of heating power alternates strongly due to the solar heat gains. Instead, the hourly demand of heating power of the atrium with the north-facing skylight stays rather constant in lack of solar gains. Hourly averages of the heating power demand of both atria during a three-day period in February are shown in Figure 10.

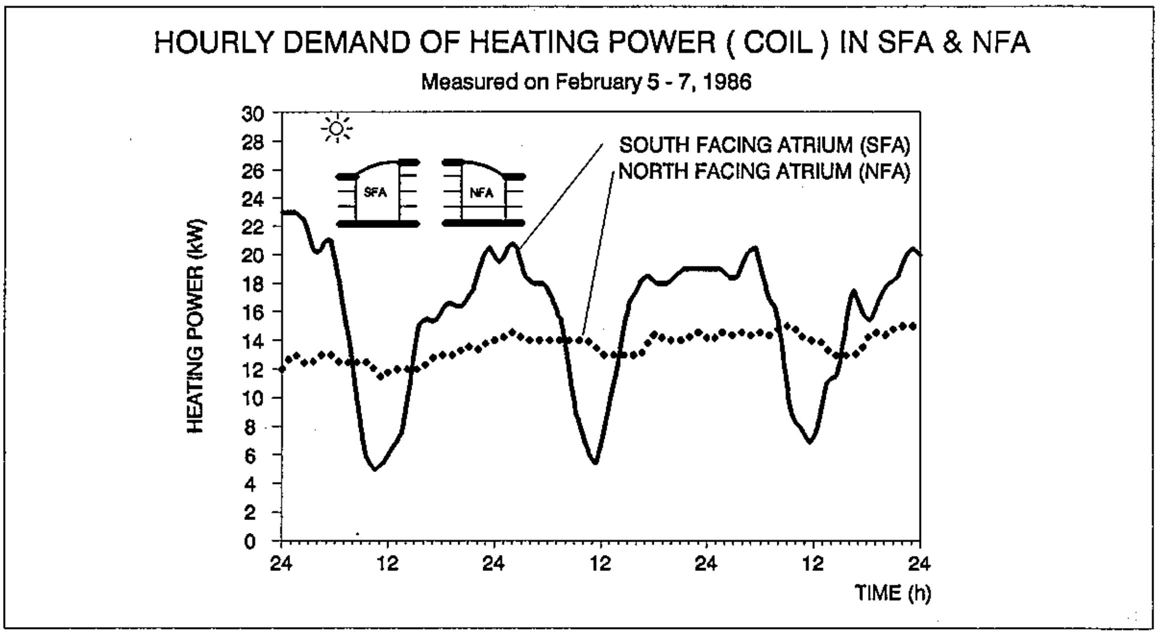


Figure 10. The Effect of the Skylight Orientation on the Heating Power Demand

Air Change Rate. The air change rate and ventilation efficiency of the atria were measured with both mechanical ventilation and natural ventilation (in the summertime). The measurements show an average of 0.6 changes per hour with mechanical ventilation for each atrium. This air change rate consist of (1) air change due to the mechanical ventilation, (2) infilteration, and (3) air change between the atrium enclosed space and the adjacent space.

The air change rate with natural ventilation was measured in both of the atria. The measurements showed an average of 0.9 changes per hour for NFA with two open air gates, 5 m^2 each, at its two top vertical glazings. The corresponding result for SFA was 0.7 changes per hour. The SFA also was measured with its main entrance doors (external doors) completely open, 4 m^2, and two open air gates, 5 m^2 each, at the top vertical glazings. The air change rate was measured to 6.9 changes per hour in the lower zone and 4.1 changes per hour in the upper zone (average of 5.5 changes per hour). The air change rate in SFA also was measured with closed entrance doors and closed air gates when the air change was limited to the infiltration and to the air change between the enclosed and adjacent spaces. The measurements showed and average of 0.3 changes per hour.

Energy Performance of the Building. The new building was occupied in September 1985. The energy consumption measurements were started after the final adjustments of the HVAC systems in the beginning of February 1986. The annual energy use of the building from February 1986 to February 1987 is shown in Table 1. The results are classified in two groups of excluding the commercial spaces and including them in order to approach more comparable figures with the energy use of the corresponding buildings. The energy use of the typical office building in Finland is about 360 kWh/m^2 and for the low-energy and best new office buildings it varies between 210 and 280 kWh/m^2. The measured energy use of the building excluding the commercial spaces was 243.9 kWh/m^2, which compares well with the energy use of the low-energy office buildings. Including the commercial spaces the energy use was 281.9 kWh/m^2.

TABLE 1. Annual Energy Use of the Building (measured)

Fuel Type	Function	Delivered Fuel	
		Total	Per Unit Area
		MWh	kWh/m2
Excluding Commercial Spaces			
District Heat	Space Heating 22 °C	652.6	92.2
District Heat	Atrium Heating 17 °C	63.8	87.1
District Heat	Domestic Hot Water	40.3	5.7
District Heat	All	756.7	96.9
Electricity	Lighting (office space)	175.0	24.7
Electricity	Other (incl. cooling)	973.2	124.6
Electricity	All	1148.2	147.0
District Heat & Electricity (Total)		1904.9	243.9
Including Commercial Spaces			
District Heat	Space Heating	1082.7	106.3
District Heat	Domestic Hot Water	71.6	7.0
District Heat	All	1154.3	113.3
Electricity	All	1716.2	168.6
District Heat & Electricity (Total)		2870.5	281.9

Simulation Results

The simulation results of the atria and corresponding open lightwells are shown in Figures 11 and 12. The simulation results show a heat-loss saving of 15 % (NFA) and 17 % (SFA) for the atria over the corresponding open lightwell (OLW) envelopes when the target temperature in the atria is 17 °C during the heating season. They also show a cooling energy use increase of 5 % (NFA) and 7 % (SFA) over the corresponding open lightwell envelopes during the cooling season, when the atria are naturally ventilated.

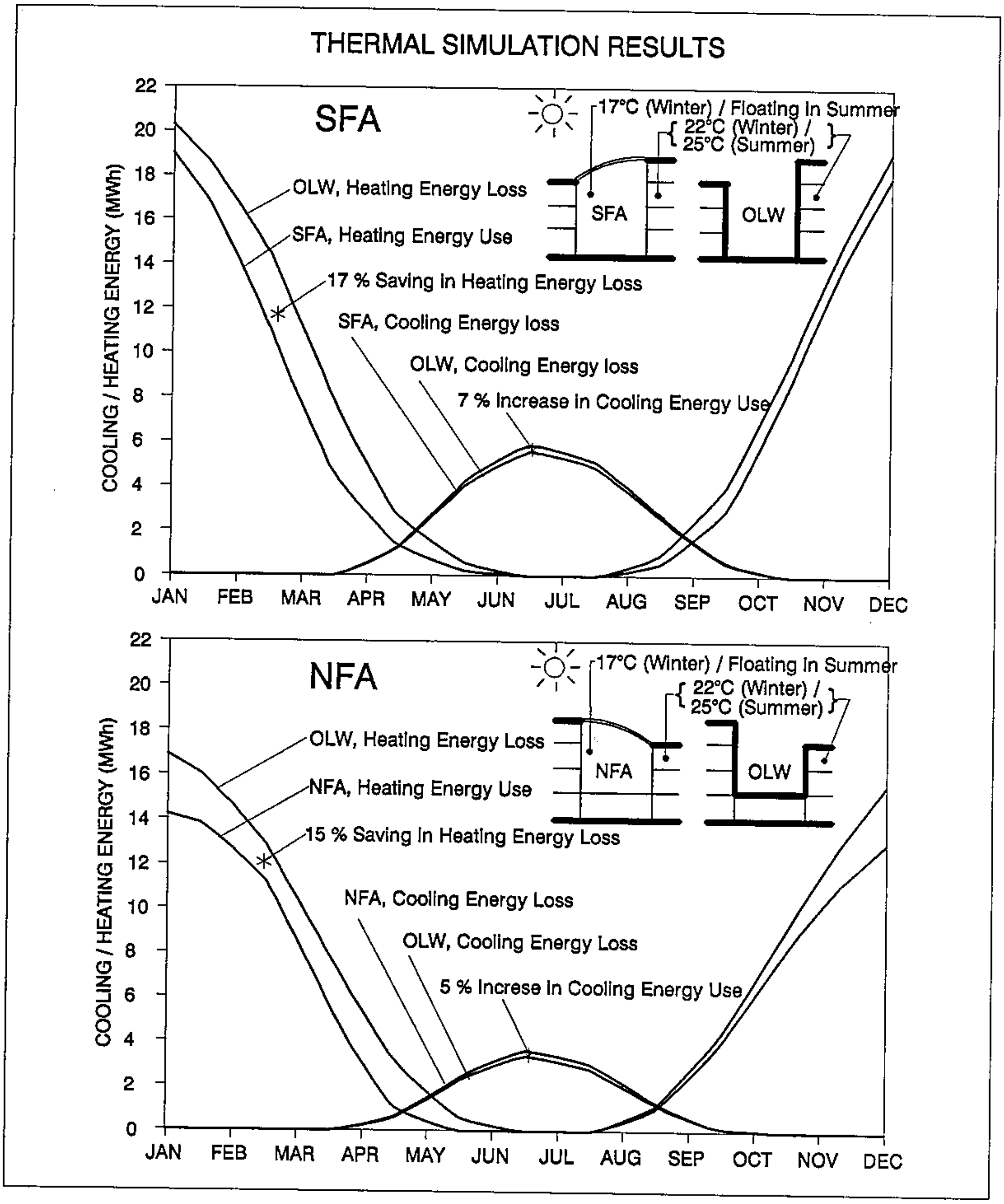


Figure 11 & 12. Thermal Performance of SFA & NFA and Open Lightwell (OLW) Alternatives

The Amenity Values

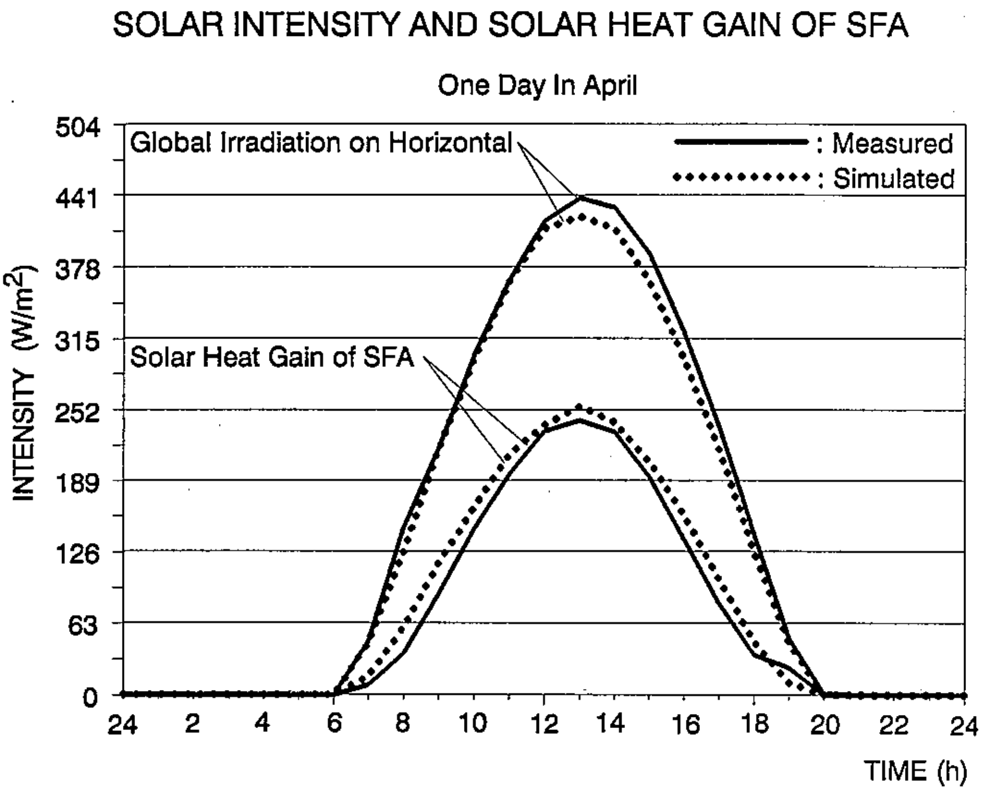
The amenity values were evaluated by interviewing the building users and owners. The interviews showed a deep satisfaction on their part. The large spaces of the atria have offered lots of opportunities for social gatherings including exibitions, staff parties, client parties, and product demonstrations for clients. The main problems with the atria had been water leakages of the skylights and noise of the fans as well as overheating in the summertime. All the problems were solved easily, but overheating required some extra openings on the entrance level of the atria to improve the natural ventilation in the summertime.

Building Cost

The building cost was FIM 3438 /m^2 gross (ECU 678 /m^2 gross) which compares well with the cost of typical office buildings in Finland, FIM 3746 /m^2 (ECU 739 /m^2). The glazing costs of the atria are covered by savings in floor area and volume of the office spaces by placing the supply and extract air ducts of the office space into the atria and using the hollow concrete slabs for ducting. Also, savings in the construction materials of the intermediate boundaries of atria are signicant. These are uninsulated structures with single-glazed windows in comparison to the standard insulated external envelope structures with triple-glazed windows for open lightwells.

DISCUSSIONS

The validity of the simulation model used in this study was examined by the measured data. The simulation results were in close agreement with the measurement results in the case study building. The average deviation was 8 % from the measured values and the maximum deviation was 21 %. The comparison of the measured and simulated global irradiation on horizontal as well as the heat gain of the atrium with a south-facing skylight (SFA) is shown in Figure 13. Measured data of the heating power demand of SFA are compared with the corresponding simulation result in Figure 14. The maximum deviations in this figure appear in the evening hours, when the pressure difference between the enclosed space of the atrium and adjacent space is changed as the air-conditioning systems in the adjacent space are stopped after work hours.



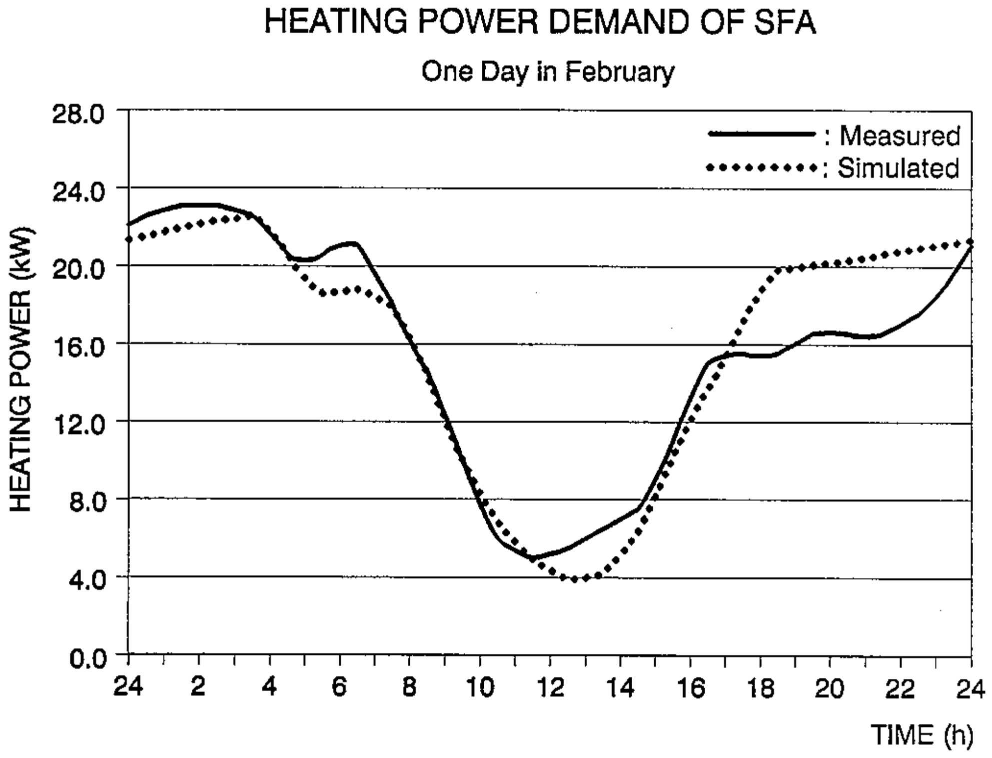


Figure 13 & 14. Validation of the Simulation Results

CONCLUSIONS

Energy performance of the case study atria and their open lightwell alternatives are analyzed and compared. The case study shows a heat loss saving of 15 % and 17 % for the atria over the corresponding open lightwell envelopes when the target temperature is 17 °C during the heating season. It also shows a cooling energy increase of 5 % and 7 % over the open lightwell alternatives during the cooling season when the atria are naturally ventilated by two air gates at the top of each atrium and the target temperature for the adjacent spaces is 25 °C.

The experimental study of the atria shows that a buffer atrium (unheated) warms up 11 °C to 14 °C over the ambient temperature by extract heat of the adjacent spaces and solar heat gains. This shortens the heating period of the atrium and reduces the heat loss of the exterior envelope of the building. This also shows the importance of the manner in which the atrium enclosed space is conditioned and its effects on conditioning of the adjacent spaces. The integration of the conditioning of the atrium enclose space and adjacent spaces (supply or exhaust air atrium) can have a significant impact on energy-saving potential. However, these strategies are very much restricted by fire safety and smoke management regulations.

Summertime heat gains and overheating of the atrium enclosed space can be reduced by openings at top and down part of the atria. Measurement results show the great influence of the location of the openings on ventilation efficiency. Overheating can also be reduced by shading devices, which may be operable or fixed. The orientation and slope of the glazing is the key factor in the amount of solar gain the atrium receives. Solar gains of a south-facing inclined glazing can reduce the heating power demand in the heating period, but it may require shading in the summertime.

Glazing of a courtyard has a significant impact on occupancy potentional of the courtyard. Enclosed space of an atrium can offer opportunities for different social gatherings which are not possible in the corresponding open courtyard to the same extension. Glazing cost can be covered by savings in the construction materials of the intermediate boundaries of the atria. Use of the atrium enclosed space for supply and extract air ducting of the adjacent space has a great saving potential in the building cost.

The overall performance of the case study building has deeply satisfied the part of the building users as well as the owners.

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ACKNOWLEDGEMENTS

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D TEGUT Advanced Case Study

Günter Löhnert

Building Type	Offices
Passive Features	
Solar heating:	Direct, indirect
Daylighting:	Direct, indirect
Occupancy Date	1985
Client	Tegut Company, Fulda

Architects
LOG ID, Tübingen
D. Schempp, F. Möllring,
W. Klimesch, J. Frantz

Construction Supervision
Heinz Wolf, Fulda

Coordination
Hoßfeld, Fa. Tegut

Monitoring
Prof. Dr.-Ing. G. Hauser, Kassel
Prof. Martin Krampen, Ulm

Floor Area	m^2
Gross:	1 000
Heated:	537
Unheated ($t_{min} = 5$ °C):	463

Building Costs	DM	1 600 000
	ECU	718 675

Delivered Fuel 270 382 MJ
(1. Sept. 1986 - 31. May 1987)

Figure 1: South facade of the building extension Photo: G. Löhnert

I. PROJECT DESCRIPTION

ABSTRACT

The project deals with the extension of the administrative building from the seventies which belongs to the Tegut company in Fulda. According to the principles of Green Solar Architecture (GSA) office pavilions have been organised on terraces covered by a large glass structure (thermal envelope). By means of subtropical planting this space represents an attractive, temporary extension of the effective office space. The effects of this innovative architectural concept upon energy consumption, thermal and hygrometric performance, daylighting conditions, and air quality have been monitored. An essential step towards "humanisation" of working areas has been made by applying creative dimensions. Human factor analysis have also been carried out and users reaction's show the success which also confirms the validity of the concept.

BUILDING DESCRIPTION

An existing office building organised as an open plan office and fitted with air conditioning had to be extended. The open plan office found approval but not the air conditioning. The new architecture should include ecological and environmental features. The company management wanted an architectural design oriented towards the future. However, the costs had to be competitive with conventional building concepts. The extension was to accommodate 40 working places. The plot available was not large enough for the building and therefore it was planned on two levels. For statical reasons the office pavilions had to be built in lightweight construction providing terraces in front of each office space accessable by glazed partition walls. To gain sufficient height a glass cube was placed at a slant and mounted onto the existing roof, touching it with one edge only. For energy reasons the larger part of the northern wall is closed off and only few windows allow a glimpse across countryside. Plants were an important factor in the improvement of the air quality and the indoor climate conditions.

SITE AND LOCATION

The administrative building of the Tegut company is located in the industrial park at the outskirts of Fulda.

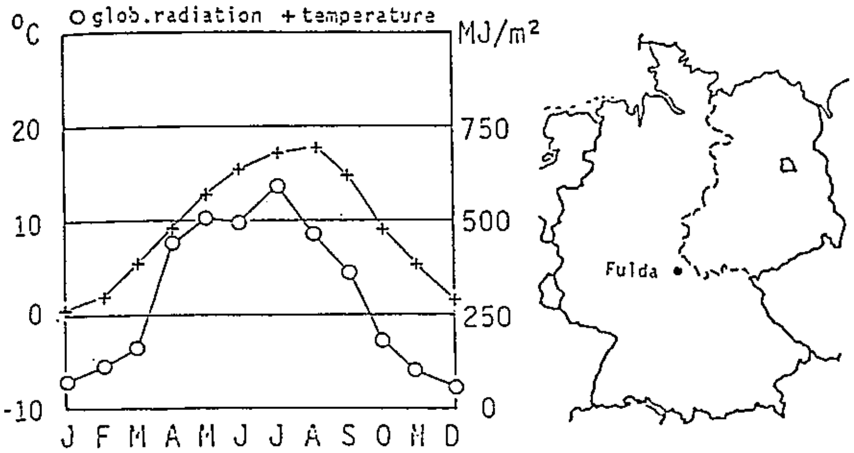

Figure 2: Global radiation and temperature development in Fulda

BUILDING ORGANISATION

The plot available was not large enough for the building and therefore it was planned on two levels. To gain sufficient height a glass cube was placed at a slant and mounted onto the existing roof, touching it with one edge only. For energy reasons the larger part of the northern wall is closed off and only few windows allow a glimpse across countryside.

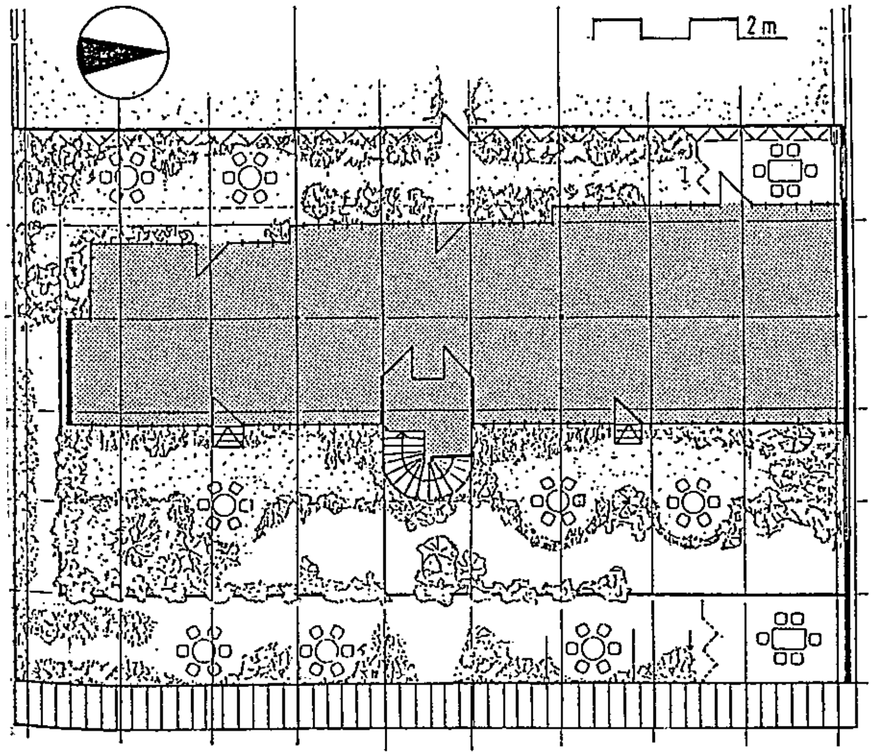

Figure 3: Floor plan

Site Data	
Latitude:	50°30' N
Altitude:	280 m

Climate Data	
Degree Days (Bad Hersfeld):	
September - May:	3 915
Annual:	4 130
Global Radiation:	MJ/m^2
September - May:	2 104
Annual:	2 787
Sun Hours:	
Actual:	1 600
Actual/theoretical:	0.36
Average Temperatures:	°C
Winter:	6.6
Summer:	16.6
Annual:	9.1

Volume	m^3
Gross:	4 785
Heated (office pavilions):	170
$t_{min} = 5$ °C:	3 615

Surface Areas	m^2
Ground floor:	1 000
Envelope:	1 247
Walls of pavilions to atrium:	377

A/V Ratios	m^{-1}
Building extension:	0.26
Office pavilions:	0.78

Glazing Areas	m^2
Exterior:	1 116
Interior:	243

Window Fractions	%
Lower office pavilion:	30
Upper office pavilion:	57

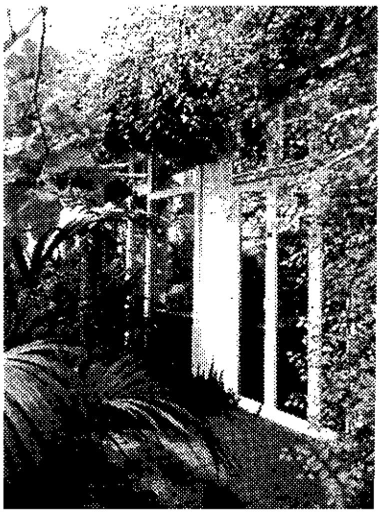

Figure 4: View to the lower office pavilion. Photo: G. Löhnert

According to the latitude a special concept was developed for the Green Solar Architecture which is the combination of a good heat-insulated house and an atrium. The atrium also represents a thermal layer, housing the office pavilions which are not affected by weather influences.

On both floors an open plan office has again been created. The working areas are screened off optically by sound-insulated dividing walls. Individual lighting underlines the separation of the various working areas. The two open plan offices are separated from the atrium by glass walls. Weather permitting, glass panels are opened and the effective area is increased by paths, conference area and the cultivated areas.

By means of the reciprocal use and the varied impressions, an interesting and ever changing space is created. Not only is its visual impression changing, but also its climate, humidity level etc. are undergoing changes.

BUILDING CONSTRUCTION

U - values	W/m^{2}K
Partition walls:	0.55
Roof of pavilions:	0.56
Floor of pavilions:	0.56
Walls of envelope:	0.36
Glazing of atrium envelope:	3.5
Windows of pavilions:	3.0

The exterior envelope of the building is a tin-coated steel structure with double-glazing. The strapping consists of lattice work to give a less solid effect. The glass cover contains four locations of ventilation flaps in the roof and the east and west walls extending the total width of the building. Each of the vents is approxiately 2 meters in length and can be opened by motors to a net ventilation aperture of 1.3 m, depending on the air temperature in the atrium. The use of healthy, non-poisonous materials was encouraged; consequently all girders are made of wood. Apart from glass, other components of the building were also made from wood. For scumbling and painting the wood only non-poisonous paints were used. All paths in the atrium are tiled.

The glass house contains relatively robust, subtropical vegetation planted directly into the soil. In this area we find evergreen plants as well as deciduous plants. Consequently, with careful planning, efficient shading can be achieved during summer and in winter light can reach the building directly. In the glass house the evergreen plants create a visually pleasant atmosphere during winter apart from oxygen generation.

Figure 5: Atrium envelope glazing and ventilation. Photo: LOG ID

These subtropical plants also require little care. Apart from bi-annual pruning and annual fertilisation they hardly require any work. An automatic irrigation system takes care of this which administers sufficient water to the plant roots. This is controlled by moisture sensors in the soil. The correct choice of plants is a prerequisite for the functioning and the independance of this biotop.

BUILDING SERVICES

The heating system of the old building could be used for the extension as well because these two gas furnaces had been oversized (total capacity 1500 kW). The existing heating system is being operated by a maximum temperature level of 75-80 °C. The building extension is seperated into two heating sections: pavilions and atrium. The system is designed as a dual system served by external temperature control. Both sections are zoned seperately in each floor. The pavilions are equiped with radiators whilst the atrium heaters are thermostatically controlled convectors. Reversely operating and revolve controlled ventilators are integrated into the partition walls of the pavilions acting for heating in winter and for cooling in summer as well. Electrical valves are installed for free ventilation between offices and atrium.

Spot-lights and hanging lamps above the conference tables provide the atrium space with a pleasant light. For the offices indirect lighting is used in addition to desk lamps. Halogen lamps directed light onto the ceiling. In addition the amount of light required can be directed individually.

PASSIVE SYSTEMS

Air heated by solar energy is transmitted into the offices by opening the doors. In addition the office walls are fitted with ventilators which suck in thermostatically heated warm air. The heating units in the offices adjust themselves accordingly. On days without sun - providing the doors are closed - only the offices are heated and the atrium temperature is allowed to drop to 10 °C. This has the advantage that only a small air volume has to achieve the temperature required for work; the outside temperature will never fall below 10 °C.

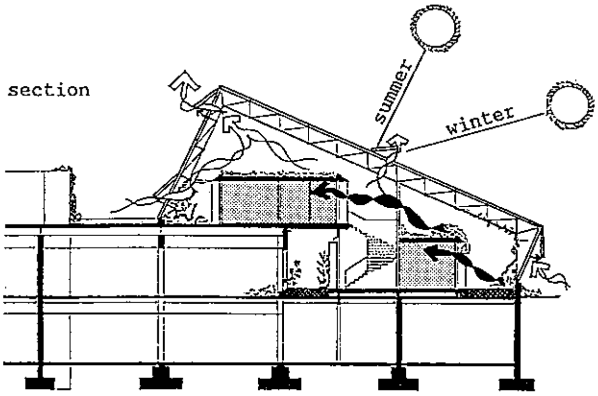

Figure 6: Atrium section

For the central heating, thermostatically controlled radiators were chosen which can be adjusted individually. These also show a fast reaction to sunlight. To prevent overheating during summer large air vents were fitted into the upright walls and the ceiling; these can be opened and closed automatically by a heat sensor. In addition, the effects of the plants - through their shading and perspiration - is that of a climate control. The roofs of the offices are well insulated and also cultivated.

The combination of all these factors makes it possible to maintain a temperature in the glass house close to the temperature outside. It is even possible to achieve an indoor temperature a few degrees below ambient.

Calculated Heat Demand

Atrium:	121 kW
Pavilions:	25 kW
Total:	146 kW

(relative to atrium temperature of 10 °C)

Installed Capacity

Space heating:	226 836 MJ

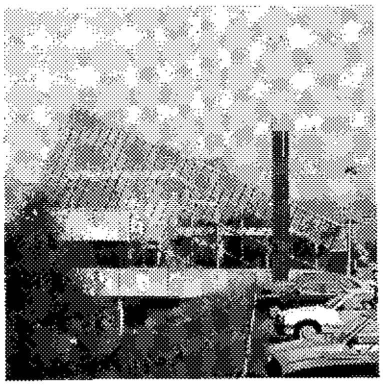

Figure 7: South view to the atrium with the terraced office pavilions
Photo: LOG ID

Design Conditions

Room temperatures:		°C
Pavilions:	day	20
	night	12
(Thermostat setting:	18^{00}- 6^{00})	
Atrium:	day	10
	night	5

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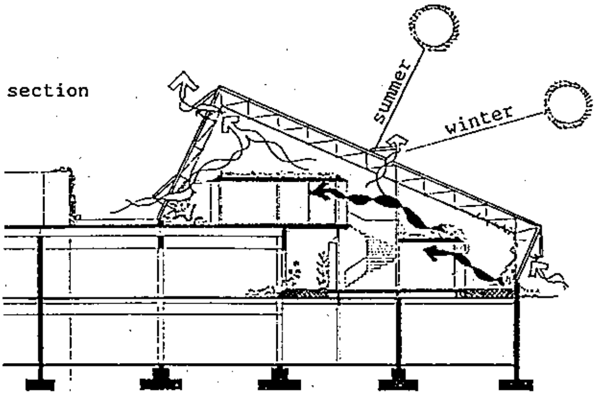

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	night	12
(Thermostat setting:	18 °°- 6 °°)	
Atrium:	day	10
	night	5

Building Costs	/m^2
Office area:	DM 3 200 ECU 1 437
Effective area:	DM 1 488 ECU 668

COSTS

The total costs of the alteration amounted to approx. DM 1.6 Millions, which is DM 3 200/m^2 for the office space, DM 1 600/m^2 for the effective area, DM 40 000 per working space.

II. MONITORING

The aim of the investigation is the monitoring of the resulting effects from this particular building concept upon heat consumption, thermal and hygrometric performance, daylighting, and indoor air quality (O_2 concentration and CO_2 concentration). Moreover amenity issues have been investigated by occupant questionaires to ascertain users acceptance relative to spacial impressions, close working space environment and health complaints.

ENERGY ISSUES

- **Monitoring Plan of Energy Issues**

Data collection of energy consumption for space heating is taken by monitoring of water flows and temperature differences between supply and return duct of the office pavilions and of the atrium heating circuit separately. Additionally, the heat fluxes to the basement and to the adjacent air-conditioned office area are also monitored. The internal gains by electrical appliances and lighting systems is considered by registration of power consumption.

Thermal and hygrometric performance of the building extension, and of the air-conditioned area to a lower degree, is ascertained by measurement of room air and surface temperatures, and indoor air humidity as well. Registration of ventilation flap aperture and air flow velocity of particular atrium areas are dedicated to assist efficiency analysis.

Figure 8: Interior view to south-east terrace area. Photo: LOG ID

The characteristic of indoor air quality is commonly given by carbon-dioxyd concentration, as for the human body the production of olfactory substances correlates significantly to the production of CO_2. Thus, the CO_2 concentration is monitored continuously. Numerous additional other factors, such as odour of plant growth are taken out of consideration. On the other hand, the oxygen concentration is measured continuously, since several previously published measurement data proclaim an expected increase of O_2 concentration for intensive greenhouse plantation. Moreover, the corresponding data and relevant meteorological parameters outside of the building are recorded as well.

The actual global and diffuse solar radiation conditions during the monitoring period are shown in figure 10 and the degree days (relative to 20 °C air temperature, daily mean ambient temperature <15°C) are represented as follows.

Characteristical numbers are:

1. Sept. 86 - 31. May 87 dd = 4.058 Kd;	Global radiation 629 kWh/m^2
1. June 87 - 31. Aug. 87 dd = 254 Kd;	Global radiation 368 kWh/m^2
1. Sept. 87 - 31. May 88 dd = 3.197 Kd;	Global radiation 537 kWh/m^2

The relevant indoor parameters mentioned above are monitored by installation of 85 sensors and continuous data recording. Daylighting measurements are executed separately for typical and representative daytime weather conditions. Power consumption is recorded by meter reading. All data are transferred to a computer unit via four HP 3421A scanners. The utilized sensors for the corresponding data collection are as follows:

Temperature:	Heraeus PT 100 1/3 DIN 4-wire measuring
Heat flux intensity:	TNO Delft WS 31
Solar incident radiation intensity:	Kipp & Zonen CM 11
Humidity:	Grillo MZF
Wind direction and velocity:	Thies Sch 1037
Air flow velocity:	angewandte Thermodynamik und Klimatechnik, Universität Essen, Gesamthochschule
Fluid meter:	Spanner Pollux Polyplus-Geber
Ventilation flaps:	consideration of voltage of ventilation flap controller
Carbondioxyd (CO_2):	Siemens CO_2 Controller TN 59 129
Oxygen (O_2):	Panametrix OX-T-19

For gas analysis method air will be evacuated continuously from the areas to be investigated and then be transferred to the analyzer after having been dried and heated or cooled, respectively due to climate box temperature. Homogeneous overall pressure is guaranteed by an air flow controller. Post-calibration of analyzer is provided each 24 hours by two gas mixtures composed of:

a) 15,4 % O_2; 84,6 % N_2
b) 20,4 % O_2; 0,267 % CO_2 and 79,333 % N_2

Daylighting investigations are executed by minilux meters by the firm Elektronik Spezial.

Failures of monitoring system or individual sensors caused by damages will be balanced by calculating the missing data by monthly values by means of linear extrapolation.

- **Energy Consumption**

Monthly heat transfer into the building extension are shown in figure xy. considering the transfer via heat emitters installed in the office pavilions and in the atrium, and the benefits from neighbouring spaces and internal heat gains regardless to those generated by occupants.

Heat transfer from the air-conditioned area includes heat transmission assessed by heat flux meters and heat by infiltration caused by opening the doors of the intermediate envelope assuming a 120 m^3/h air change during office hours ($6^{\circ\circ}$ - $18^{\circ\circ}$) and that the temperature difference between the conventionally conditioned area and the staircase is relevant. Heat transfer from basement is measured for representative locations by heat flow densities and increases due to warm seasons when cooling engines run continuously.

The continuously monitored data are recorded by cycles of 15 minutes and include the following:

Instantaneous Values:
Temperature (excluding the supply and return temperatures of heating circuit), humidity, wind direction, and gas concentration.

Quarter-hourly Mean Values:
Solar incident radiation intensities, wind speed, heat flux and supply and return temperatures of heating circuits, aperture of ventilation flaps by registration in sequences of 18 seconds.

Half-hourly Mean Values:
Heat flux intensities and heat flow velocities in the atrium by 36 seconds recording mode.

Figure 9: Interior view to the upper pavilion. Photo: G. Löhnert

Annual Fuel Use	MJ/m^2
Gross:	270
Heated:	503

Figure 10:
Monthly Energy Flows of Heat Contribution: Seasonal development of heat transfer in the atrium office extension to ambient climate conditions

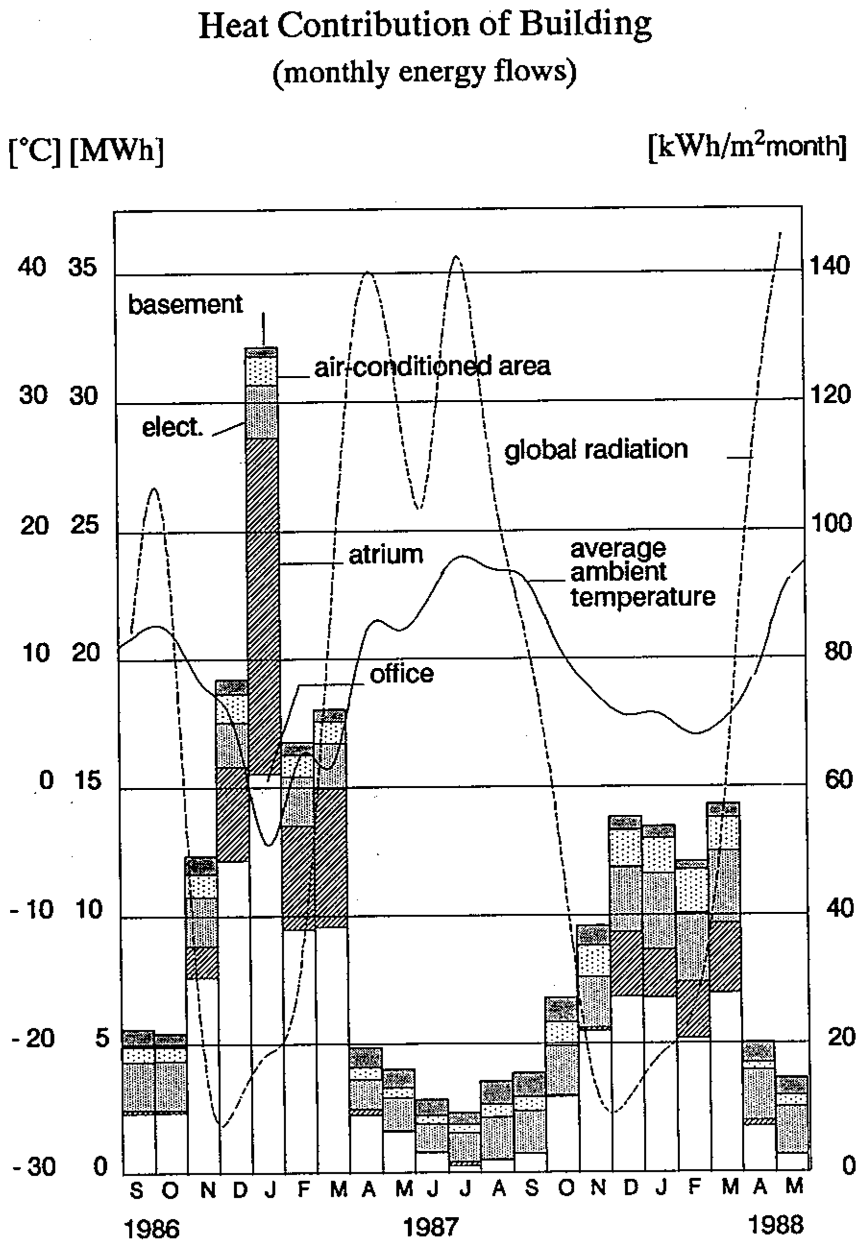


Figure 11:
View from the upper floor level to the atrium. Photo: G. Löhnert

A comparison of total heat transfer and degree days shows a proportionally corresponding situation; considering solar contribution opposite tendencies are remarkable: In december 1986 (537 dd) the heat transfer is higher compared to march 1987 (625 dd) resulting in different incident solar radiation conditions (december 1986 = 11 kWh/m^2; march 1987 = 81 kWh/m^2). The following table shows the total heat delivery during the heating periods and the summer season:

heat contribution	**winter 86/87**	**summer 87**	**winter 87/88**
office pavilions	63.86	1.65	37.71 MWh
atrium	28.20	0.18	9.14 MWh
electricity via AC area	6.21	1.07	7.53 MWh
from basement (=first floor)	5.04	1.92	5.79 MWh
Total	119.09	8.77	80.74 MWh

Although the global radiation has decreased by 15 % the heat contribution of the heating period in 87/88 is 32 % less in comparison to the value of the period in 86/87. The reason for this fact is

- degree days are 21% lower
- air room temperature of pavilions have been adjusted 1K lower
- extra insulation at the northern wall was installed in may'87

A reasonable base of comparison is the relation to the heated area which is 536.6 m^2 in total. Apart from that, an area of approximately 71.3 m^2 is at least temporarily usable in a similar kind of way.

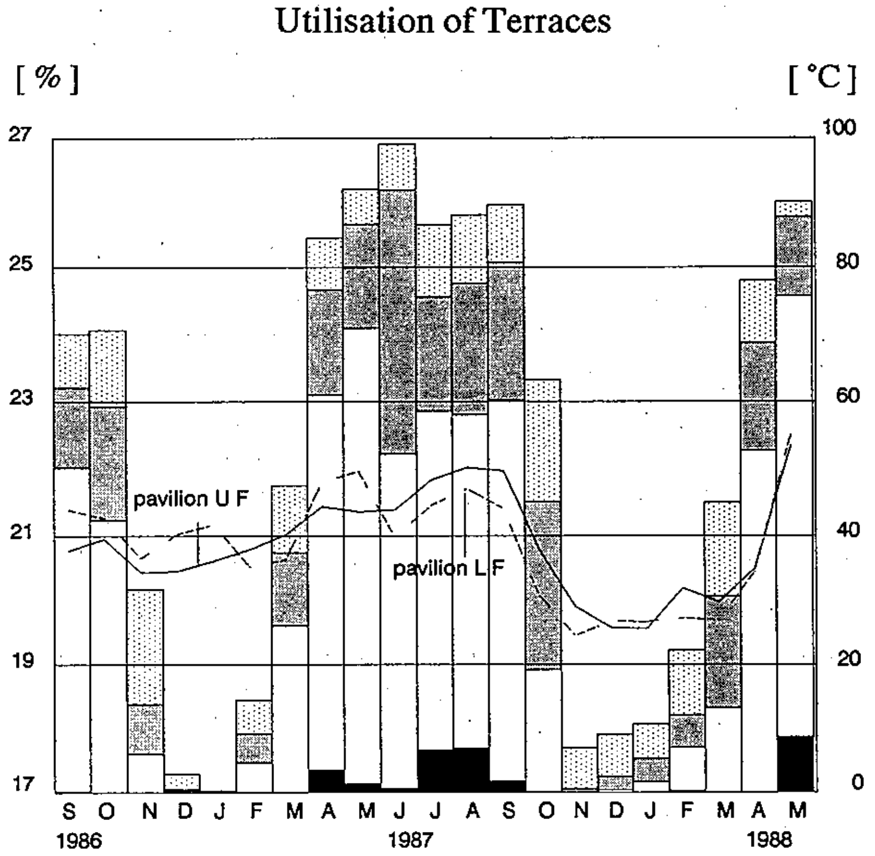


Figure 12:
Utilisation of terraces relative to different comfort levels according to average indoor temperature development of upper floor (UF) and lower floor (LF) office pavilions during monitoring period.

caption:

16 °C to 28 °C ░

18 °C to 28 °C ▓

20 °C to 28 °C □

above 28 °C ■

Figure 13: Terrace planting in front of the upper office pavilions.
Photo: G. Löhnert

A quantification of limited utilization of spaces is generally difficult. For this case, however, a quantified definition by relative duration of space use seems to be adequate (see figure 12).
This relative temporal use considers a period of time when air temperature is below 28°C and above 20 °C, or 18 °C, or 16 °C, respectively, during the office hours from 7$^{\circ\circ}$ - 17$^{\circ\circ}$. Since the relative temporal use of of the different areas do not differ so much a mean value will be considered representing the total usable area. This average multiplied by the total area of 71.3 m^2 will give a comfort zone- and usability-weighted countable extra space for one year as following:

air temperature	relative temporal use	extra space
> 16 °C	57.2 %	40.8 m^2
> 18 °C	48.1 %	34.3 m^2
> 20 °C	33.0 %	23.5 m^{22}

Considering the mean value the total area will be 536.6 m^2 + 34.3 m^2 = 570.9 m^2 . Thus, the specific heat consumption during one year will be 157 kWh/m^2 a. Relating the heat consumption to the degree days a value of 0.045 kWh/m^2 Kd will result.

Mind that the total of delivered heat to the system has been considered. However, part of the heat contribution by electricity and heat transfer from the adjacent air-conditioned areas, or from the basement, respectively, also occurs at times when space heating is not required. Thus, taking these influences out of consideration, the modified values will be 85 kWh/m^{2}a und 0.025 kWh/m^{2}Kd.

It is impossible to assess exactly the usable sectoral ratios of electricity, air-conditioned area, and basement by monitoring. Thus, most reasonable seems a general consideration of heat flow from the conventionally conditioned area and from the basement with regard to the following figures:

- excluding electricity: 114 kWh/m^{2}a (0.033 kWh/m^{2}Kd, resp.)
- including electricity: 157 kWh/m^{2}a (0.045 kWh/m^{2}Kd, resp.)

However, even these values do not consider solar energy inputs. Moreover it should be recognized that the monitored data represent the energy consumption not the fuel consumption. Consequently the boiler efficiency and the waste gas losses are not recorded as well. For comparison purposes the measurement data will be modified by consideration of a mean boiler efficiency of 88% and a waste gas loss of 10% providing the following data:

- excluding electricity: 144 kWh/m^2 (0.042 kWh/m^{2}Kd, resp.)
- including electricity: 187 kWh/m^2 (0.054 kWh/m^{2}Kd, resp.)

Aside from the total annual heat consumption the instantaneous values of heat consumption depending on extreme outdoor temperature conditions is of particular interest (see figure 14).

Figure 14: Daily development of heating capacity delivered to office pavilions and atrium at the coldest day of monitoring period

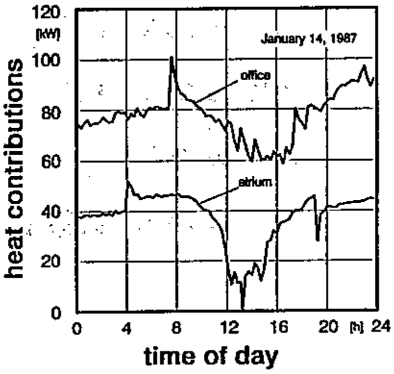


Figure 15: Temporal working space at communication terraces of the upper floor. Photo: G. Löhnert

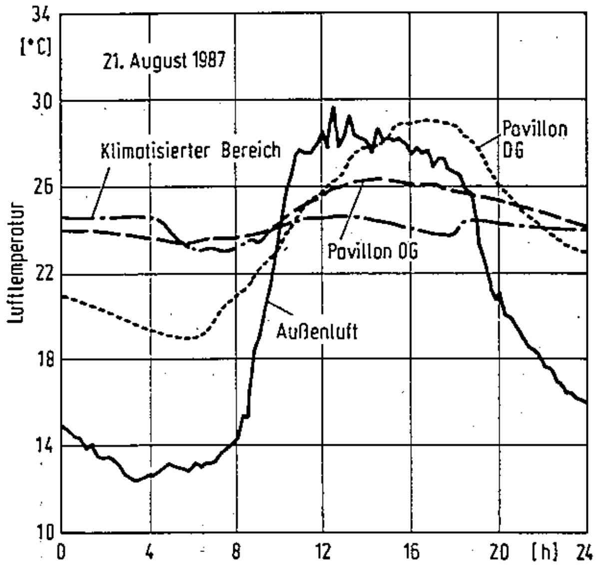
- **Temperature Performance**

During the office hours the indoor air temperatures of the individual building areas are kept on a certain minimum level by the heating system; for higher values the building extension is freely floating while the air-conditioned office area of the old building will be cooled mechanically to avoid overheating.

The frequency of individual air temperatures during working hours are shown for seasonal development in figure 14.

Maximum temperatures in an office area occured in the upper pavilion (29°C) on August 21, 1987. The corresponding diurnal temperature development is shown in figure 17. The correlating ambient temperature rises up to 29.6°C and the global radiation receives a maximum of 800 W/m^2 (see figure 18).

Moreover the temperature conditions in the atrium for hot summer days are of specific importance (see figure 16 and 17).



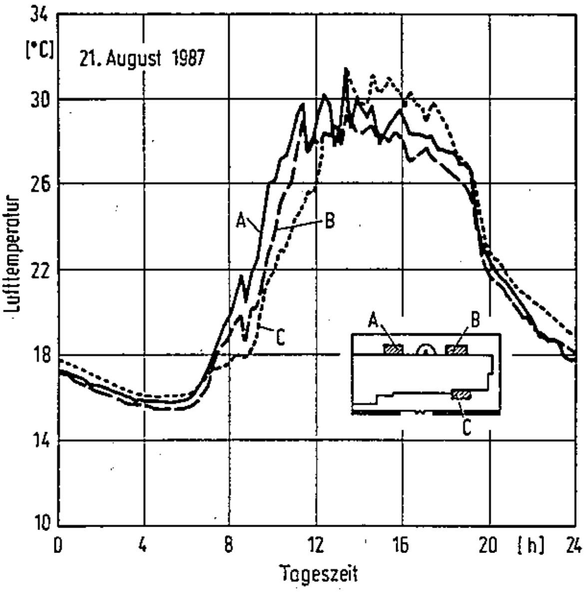


Figure 16: Diurnal development of indoor air temperature relative to different office areas and ambient air temperature for the highest indoor temperatures (upper pavilion, August 21, 1987)

Figure 17: Diurnal development of corresponding indoor air temperatures at the communication terraces on the same day (August, 21, 1987).

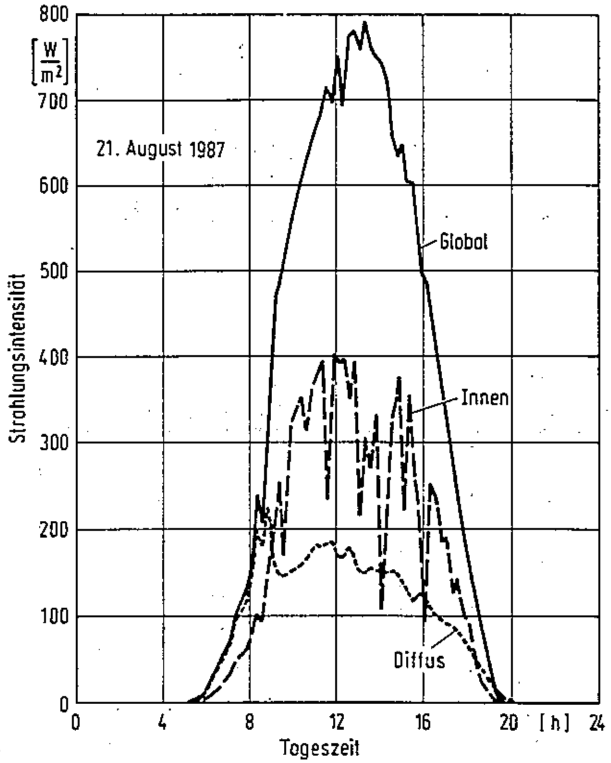
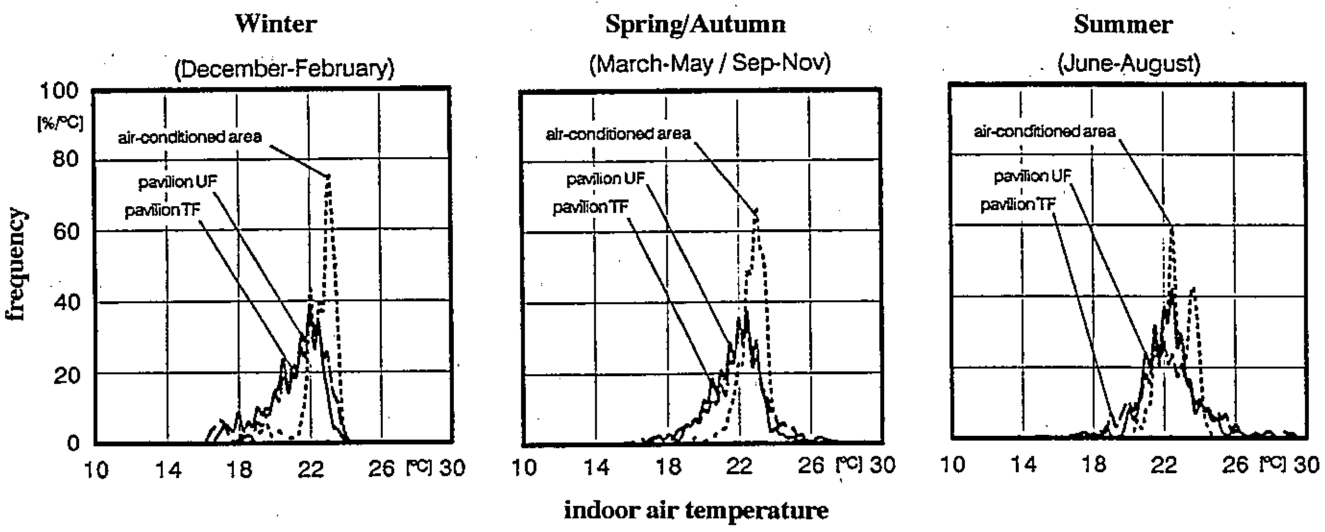


Figure 18: Diurnal development of solar irradiation intensities (August, 21).

Figure 19: Seasonal development of indoor air temperature frequencies relative to different office areas during working hours (7°°-17°°).

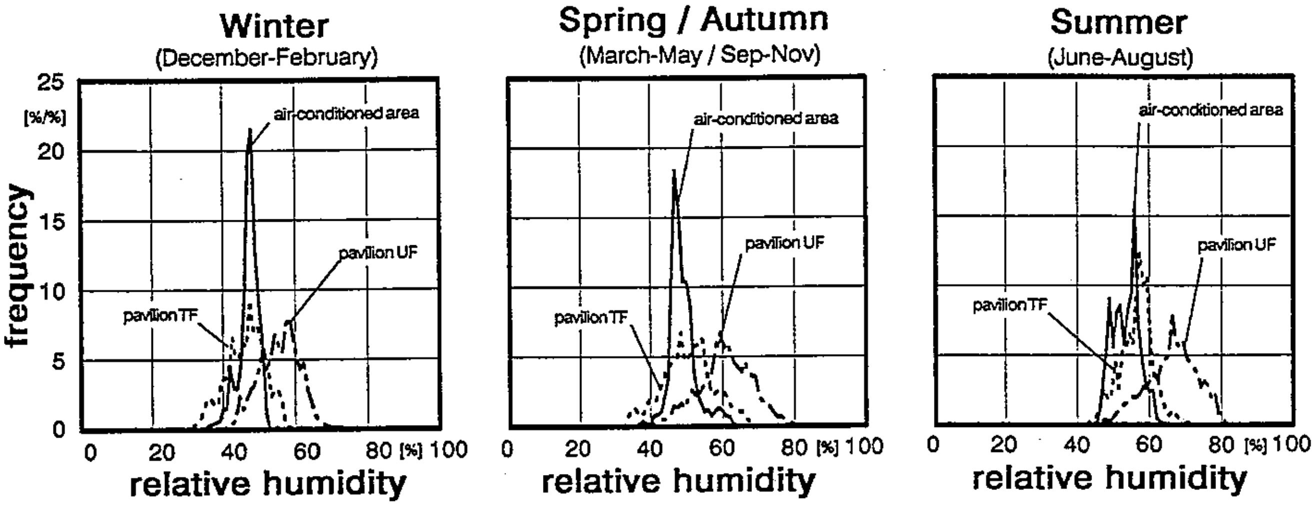


Relative Humidity	%
Pavilions:	40-65
Atrium:	up to ambient

Figure 20: Frequency of seasonal distribution of relative humidity according to different office areas of the Tegut building.

- **Development of Humidity**

For the given building the development of indoor air humidity levels are of particular interest. Relative humidity values should not exceed the recommended levels of 40-60% valid for living rooms and office spaces. Figure xy represents the relative humidity according to the seasonal development for different office areas.



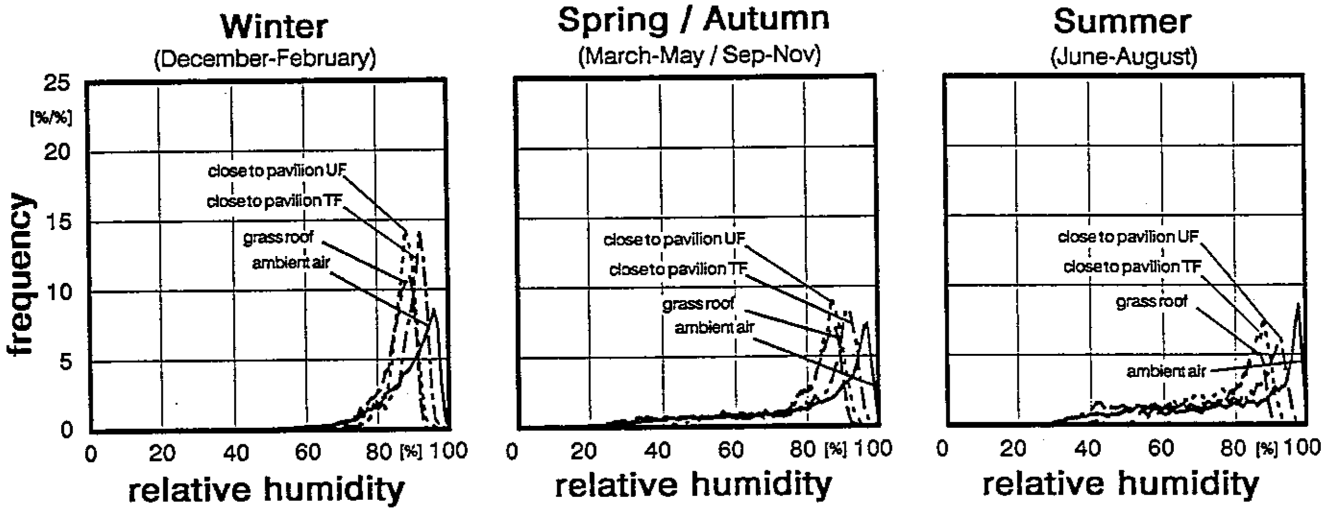


Figure 21: Frequency of seasonal distribution of relative humidity according to different atrium areas.

- **O_2 und CO_2 Concentration**

Several literature sources attribute an subsantial influence upon oxygen and carbondioxyd concentration for the air of adjacent spaces to an intensive plant growth in glasshouses or atria respectively.

In order to prove this effect, measurements of O_2 and CO_2 concentration have continuously been recorded for the office pavilions at both levels and at representative locations within the conventionally conditioned office area and for ambient air (at the roof) as well. The results will be discussed as follows:

O_2 Concentration:

There is no significant alteration in O_2 concentration in the office spaces adjacent to the atrium related to outdoor O_2 concentration levels. Alterations of some hundredth parts of volumetric percentage can be indicated as not being existent.

Content of Oxygen	%
Pavilions:	21

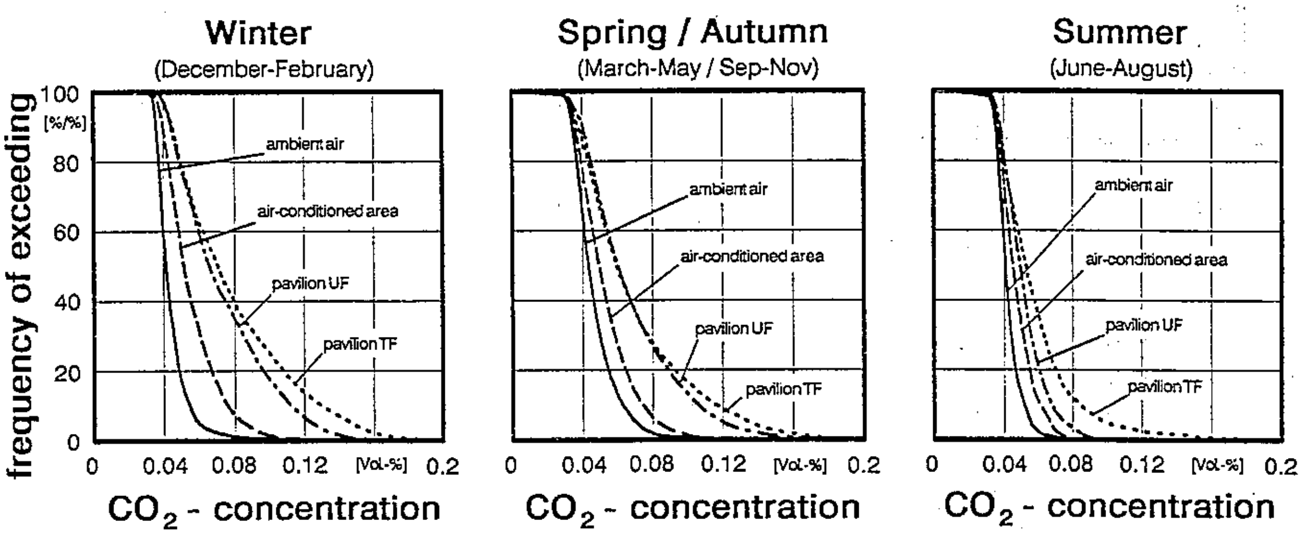
CO_2 Concentration:

Description of indoor air quality related to olfactory substances and perspirations by occupants is commonly evaluated due to Pettenkofer by means of CO_2 concentration. However, it is not possible to make any statements concerning dust pollution of the air, poisonous or disturbing gases transferred by outdoor air and/or generated by working processes in the working space, and any olfactory effects by plantation.

Thus, CO_2 concentrations are a predestinated indicator for olfactory inconvenience and provide information about the supply by outdoor air for the indoor spaces.

Since concentration levels during the time of occupancy from 7 °° to 17 °° are of major interest the frequencies of this period is shown in the figure below.

Figure 22: Frequency of seasonal exceeding of CO_2 concentration in (vol%) relative to the mandatory limits (0.15%) in different areas.



• Daylighting

Availability of daylight for office spaces is of great importance concerning the quality of utilization and for operating costs. Since glasshouses and atria generally reduce the daylight illumination levels for the receiver area in adjacent spaces, the conditions for this case of envelope atrium building has also to be investigated.

A total of 117 points of measurement have been fixed and installed considering the location of existing desk working spaces. Recorded data can only be compared resulting from a very narrow period of time, as caused by manyfold variations of movable interior partition walls by the occupants. The measurements have been taken under overcast sky till sunny weather conditions. Corresponding daylight factors in the office pavilions for covered to clear sky conditions on September 19, 1987, 10°° - 13°° are shown below:

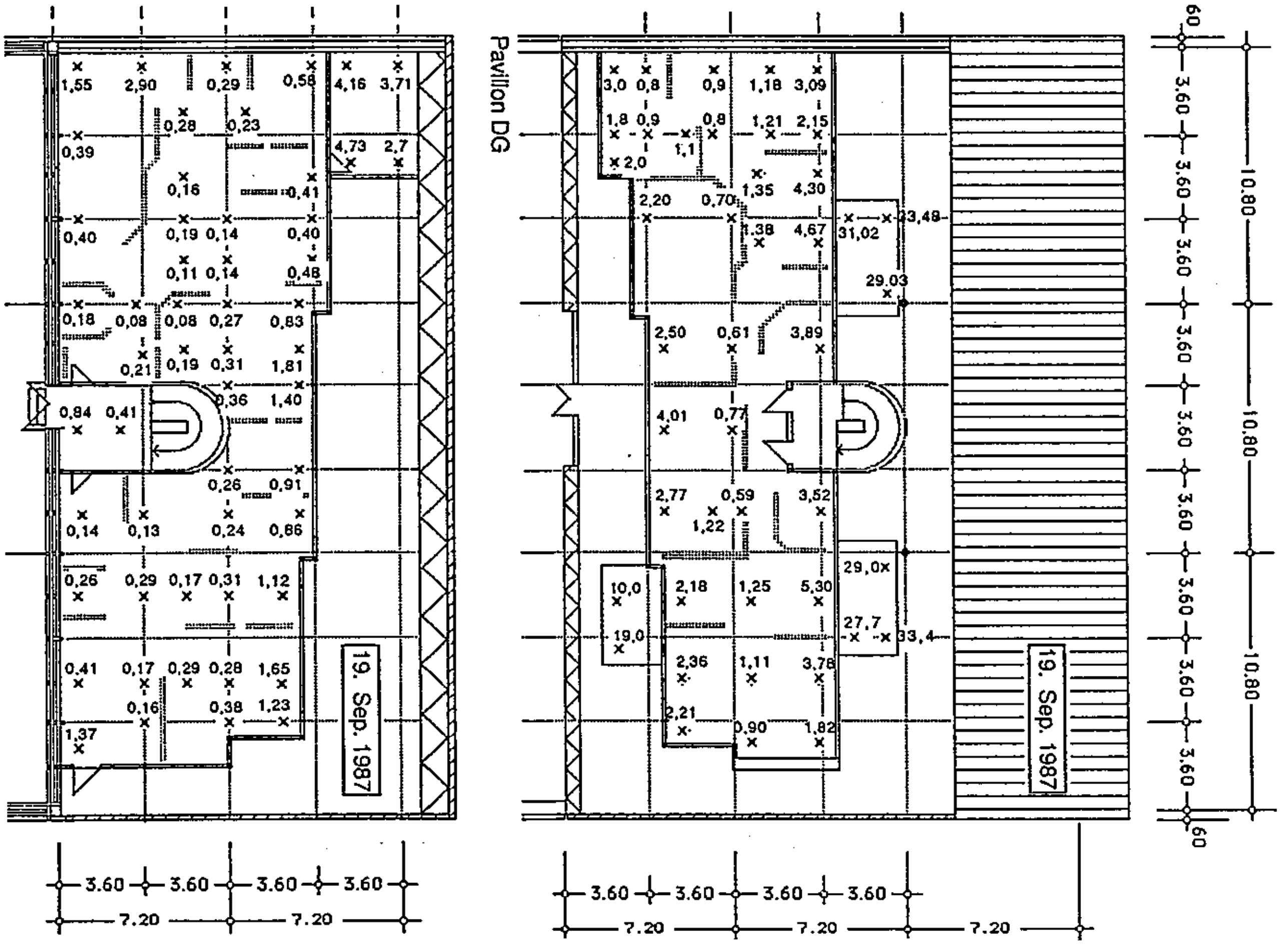
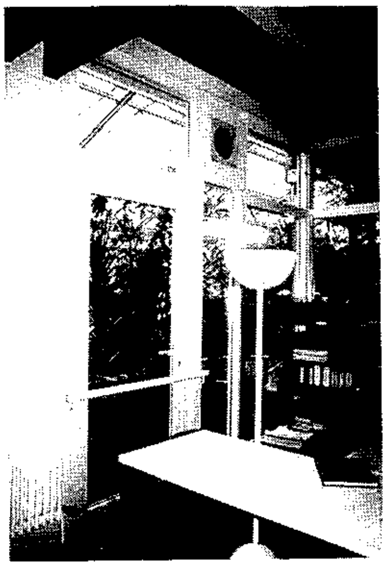


Figure 23: Daylight factors in the office pavilions for covered to clear sky conditions on Septeber 19, 1987

Figure 24: View from an office space via the intermediate envelope
Photo: G. Löhnert



These results can be interpreted as follows:

The recorded daylight factors due to the individual locations in the office pavilions did not differ very much related to the points of time when different weather conditions occured while the variations of those in the air-conditioned area were higher. In cases of deviation, higher daylight factors established for lower outdoor illumination levels. Direct sunlight will be diminished by the glazed building envelope to a higher extent than diffuse solar radiation. Exceptions occur for a few locations very close to the facades and which partially receive direct sunlight. Maximum daylight factors have been recorded at the eastern communication terraces of the upper floor level with an absolute value of 33.5%. Daylighting factors of 10% and more will be received at the western terraces and in the air-conditioned office area at particular locations very close to the southern facade.

The most important consideration in this case study, however, is the interdependancy of daylight availability and shading effect. As the intensive plantation is responsible for both, the control of plant growth directly affects thermal and daylighting comfort levels.

AMENITY ISSUES

The objective of the investigation was intended by a comparative analysis of the impressive effects upon the occupants of a conventional air-conditioned open plan office and the attached envelope atrium office.

The comparative issues included the overall impression related to the different office spaces as well as the close working space environment upon the occupants. Moreover, a comparison of individual physical health complaints and the mood of people were to be investigated depending on the different spatial situations.

The questioning also intended a methodical target: In the autumn of 1985 the all occupants of the conventional office building were interviewed before part of them moved to the atrium office extension. From that day on, both situations have been investigated by four reiterative interviews in order to assess possible modifications of findings over the two years. These interviews were carried out in the springs and summers of 1986 and 1987.

• Background of the Study

Most of similar investigations concerning the interior space impressions upon occupants are related to residential spaces (eg. Peel 1982). As a method of investigation particular constellations of scales have been established containing polarized adjective pairs. These indicators could be found by a systematical search through literature about aethetics, architecture, and interior design. Using an instrument like this EDS (Environmental Description Scale), four dimensions of spatial experience have been established: Aesthetical attractivity, physical organisation (e.g. order), spatial size, and temperature and ventilation, respectively (Kasmar 1970). Experimental investigations from other sources about spatial impressions of space variants allow to establish the following evaluation factors, dedicated to an idealized space configuration: Originality, Naturality, Size, Playfulness, and Quiet.

Open plan offices have also been investigated by scales of adjective pairs, but mostly the results were disadvantageous for this office type.

Experiences about spatial impressions of exterior and interior aspects concerning the concept of Green Solar Architecture (GSA) are fairly young. In 1984 Jäger investigated the effects of GSA upon 10 families who were living since 3 - 17 months in new residences or attached homes designed due to this concept. He used a translated and adapted version of the EDS method and the most significant impressions concerning the glasshouses can be described as: progressive, natural, attractive, imaginative, inviting, animative, up to date, varied, and healthy. Climatic impressions included: fresh and good odour, bright, good visual comfort, colourful and fresh.

Szecsenyi (1986) used for one investigation done by the method of Repertory Grid after Kelly (1955, 1963) photographies illustra-

Figure 25: Subtropical planting of terraced pavilion roof garden.
Photo: G. Löhnert

Design Occupancy
40 persons

Functions
Office, work

Time of Occupancy
8 °° to 18 °°
flexible working times
5 days per week

Figure 26: View to the eastern entrance area. Photo: G. Löhnert

ting exterior aspects of conventional detached residences and compared them with those containing buildings according to the concept of GSA.

Here, the factors of evaluation included the dimensions of General Judgement (like "interesting", "animating", etc.), Harmony, Style, Originality, Brightness, and Choice of Material. In comparison to conventional residences, buildings addressing Green Solar Architecture were definitely the favourites. A comparison of interior spatial arrangements of GSA buildings shows that occupants prefer a fairly disciplined arrangement / distribution of plants which do not cover a too large space.

Consequently the results of the studies by Jäger and Szecsenyi have influenced the method and questionaires of the Tegut building investigation concerning the impressions of office spaces and working space environments.

• Health Aspects for Open Plan Offices

A widely spread opinion says that conventionally full-conditioned open plan offices produce a disadvantageous health condition for the occupants. Serving as an example, the scientific investigations to this subject have been done at Technical University of Munich (1985) on behalf of the German Federal Ministry of Research and Technology. This study about "Feeling of ill-health and discomfort in conventional and air-conditioned buildings..." results in the fact that "people working in air-conditioned environments tend stronger than others to rheumatic complaints, weakness of blood circulation, headaches, tiredness, weariness, and allergies".

Other reports about the same study (Kröling, in "Der Spiegel" 1985) state that there are "....approximately one dozen factors responsible for the existence of the Building Illness Syndrom. Unpleasant odours can be produced by mechanical filters and by circulative spray-humidification which also provide an ideal fertile soil for mould and (sea)weed. High air change rates in fully conditioned spaces whirl up dust and induce allergies frequently. Draft air flows generated by different physical processes of climatisation could be responsible for abundant common colds and the irritation of mucous membranes."

Figure 27: Lower office pavilion
Photo: G. Löhnert

The Tegut questionaires also include parts of those aspects concerning the feeling of ill-health.

• Emotional Attitude and Spatial Impressions

Previous studies by Espe (1982) and Hampel (1977) have shown a relationship between the emotional attitude and the spatial impressions of occupants related to experimental spaces and idealized space imaginations. Emotional safety is disproportional to bad mood and the disposition of indolence and tiredness. Bigger spaces are favoured according to positive emotional disposition of occupants. To the same degree the requirements for emotional safety decrease simultaneously.

This phenomenon is also to be studied by relating the emotional attitudes to the impressions of the total space and the close working environments of both the existing open plan office and the attached atrium office pavilions.

Evaluation of occupants' mood has been assisted by a modified series of adjectives after Hampel (1977) containing a reduced number of only three adjective features.

- **Hypothesis**

Spatial Impressions:

Previous studies have shown that there are negative influences upon spatial impressions for open plan offices and positive results for GSA building concepts. Thus, in this study different evaluations have been expected for the different office areas in favour of the atrium working spaces.

Working Space:

Similar reasons may lead to the assumption that the close working space environment of the atrium office will differ positively from that of the air-conditioned area.

Individual Sensation of Health Complaints:

Different indications of symptoms of health complaints can be expected according to the different spatial situations, due to the results of previous studies mentioned above. Especially the common cold symptoms in the atrium office area are supposed to be significantly negligible.

Emotional Attitudes:

As instantaneous mood effects spatial experiences it can be supposed that there will be different results according to the variations of spatial appearances of both office areas. If the atrium office causes a more roomy impression compared with the open plan office, a closer correlation to positive moods can be expected.

Enduring Effects:

The different impressions of space and working environment of both conventional office and atrium office should last between the individual interviews. Enduring effects have also been expected concerning the listed symptoms of health complaints correlated to the spaces and working environments, respectively, as well as the correlations of emotional attitudes to space and working place.

Selected group according to interview sequences:

	summer 85	spring 86	summer 86	spring 87	summer 87
old building	117	53	46	79	63
atrium		22	16	26	17
Total	117	75	62	105	80

Figure 28: Communication terrace
Photo: G. Löhnert

The table shows the number of people who have been interviewed at different times and different office areas. It should be considered that a great fluctuation occured in the atrium caused by the run of occupants from the conventional offices on the new atrium offices. The high attractiveness of the atrium office pavilions induced the management to create an occupancy rotation mode which enabled most of the company stuff to work in the new spaces at least for six months. This is the reason why only seven occupants of those who have moved into the atrium in spring 1986 would stay there until summer 1987.

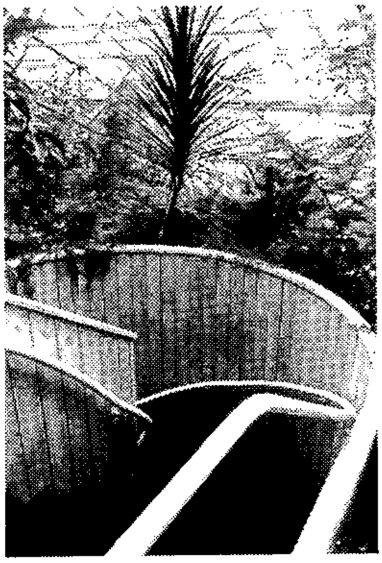
• Inquiry Method

To assess the acceptance of the new atrium office pavilions in a first step the employees of the Tegut Company were interviewed collectively in the old building before the atrium was finished (autumn 1985) and then in a series of four interviews separately for those who have been working in the conventional building and those working in the atrium offices.

For all four carried out interviews identical rating scales have been used to assess the impressions of the total space, of the close working environment as well as individual valuations of feeling of ill-health and instantaneous emotional sensations (mood). The data have been evaluated by factor-related analysis method, separately for the individual interviews, and as a total for all comparative times of interviews.

The differences of both the data from the air-conditioned area and the atrium offices have been checked by t-tests for statistical significance. Considering factor values, correlations have been calculated concerning the factors of "impressions of total space" and "close working environment" and the factors of "feeling of ill-health" and "emotional sensations" as well. Additionally, a number of seven employees working in the atrium office pavilions have been compared to a similar group in the conventional building for a long-term experiment over all five interview sequences.

Figure 29: Stairway connecting the two office levels. Photo: G. Löhnert



• Data Analysis

First of all, the four joint scales of the aspects "impressions of total space", "impressions of working environment", "health complaints", and "emotional attitudes" have been calculated separately by factor analysis according to the interview sequences. Then, an overall factor analysis has been carried out for the four sets of scales and for all five measurement periods. For comparative purposes of the open plan office and the atrium office pavilions the significance of the average factorial difference related to the resulting factors have been examinated by t-tests. Moreover, an ex-post experiment compared the seven persons working continuously in the atrium office pavilions all over the time to another seven persons paired by control consideration which have been working in the conventional office building during all the time of the study.

- **Results**

Similar factorized structures have been found for both the individual interview sequences and the total data collection, and for the long-term study as well. Four factors are significantly important for the dimensions:

For the dimension "feeling of ill-health" three factors have been recurring, generell nervousness, complaints concerning cardiovascular impairment, and common colds. The dimension "emotional sensation" can be characterized by good mood and bad mood.

The greatest significant differences (p<.001) concerning "impressions of total space" in favour of the atrium office pavilions are valid for all interview sequences as follows: original vs. dull, good atmosphere vs. bad atmosphere, appealing vs. unfriendly, natural in appearance vs. technical in appearance, vital vs. spiritless, well balanced vs. unbalanced, colourful vs. colourless (see figure 30).

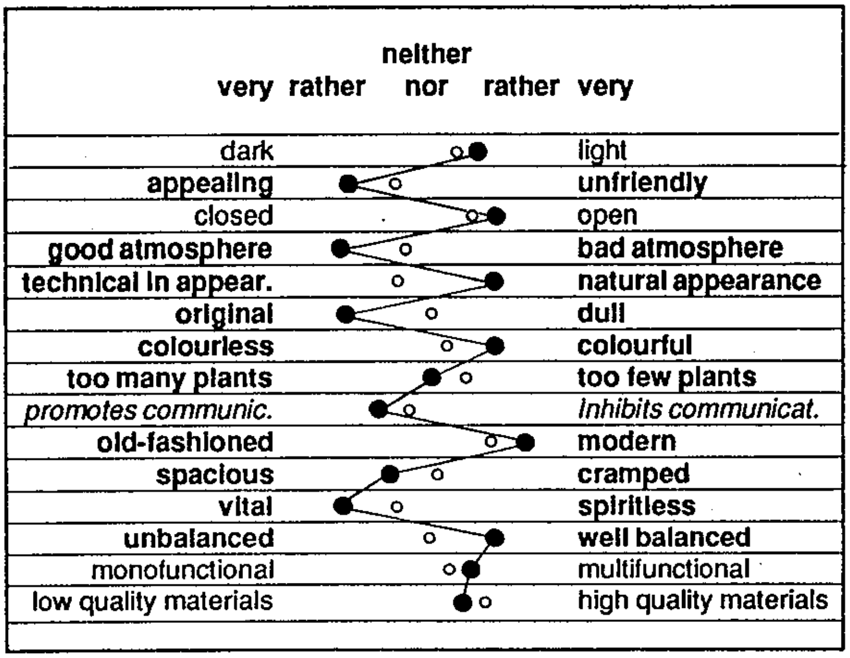


Figure 30:
"Impressions of Total Space"

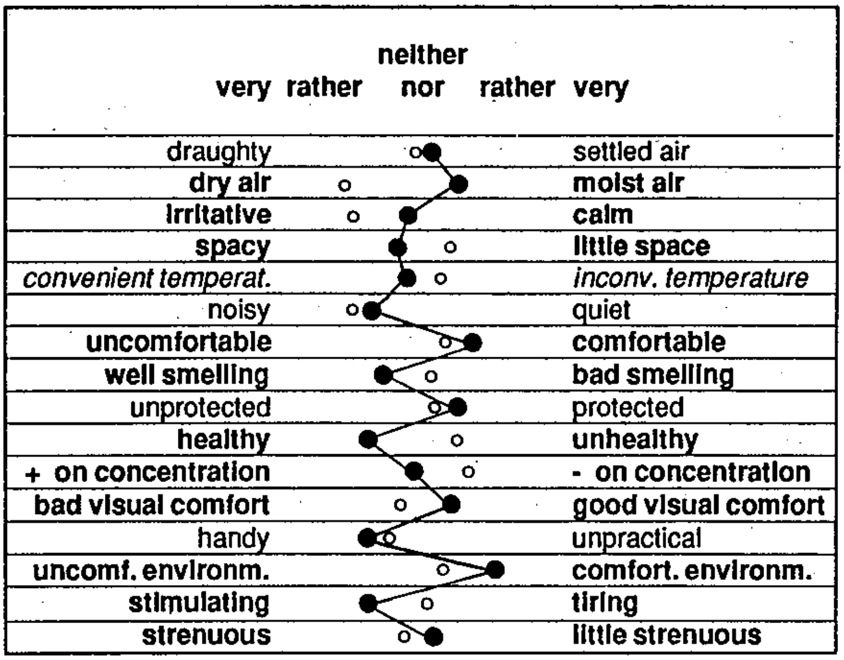
○ ○ ○ Air-conditioned area
●——● Atrium Pavilions

Significances: **bold** = $p < .001$
italic = $p < .050$

Concerning the "impressions of working environment" the greatest significant differences (p< .001) are also in favour of the atrium office pavilions as follows: healthy vs. unhealthy, well smelling vs. bad smelling, moist air vs. dry air, convenient temperature vs. unconvenient temperature, stimulating vs. tiring, bad visual comfort vs. good visual comfort.

Impressions of total space:	dullness	versus	originality
	multifunctionality	vs.	monofunctionality
	good materials	vs.	bad materials
	brightness	vs.	darkness
Impressions of environment:	handy	versus	unpractical
	quiet	vs.	noisy
	healthy	vs.	unhealthy
	draughty	vs.	settled air

Figure 31:
"Impressions of Direct Working Environment"

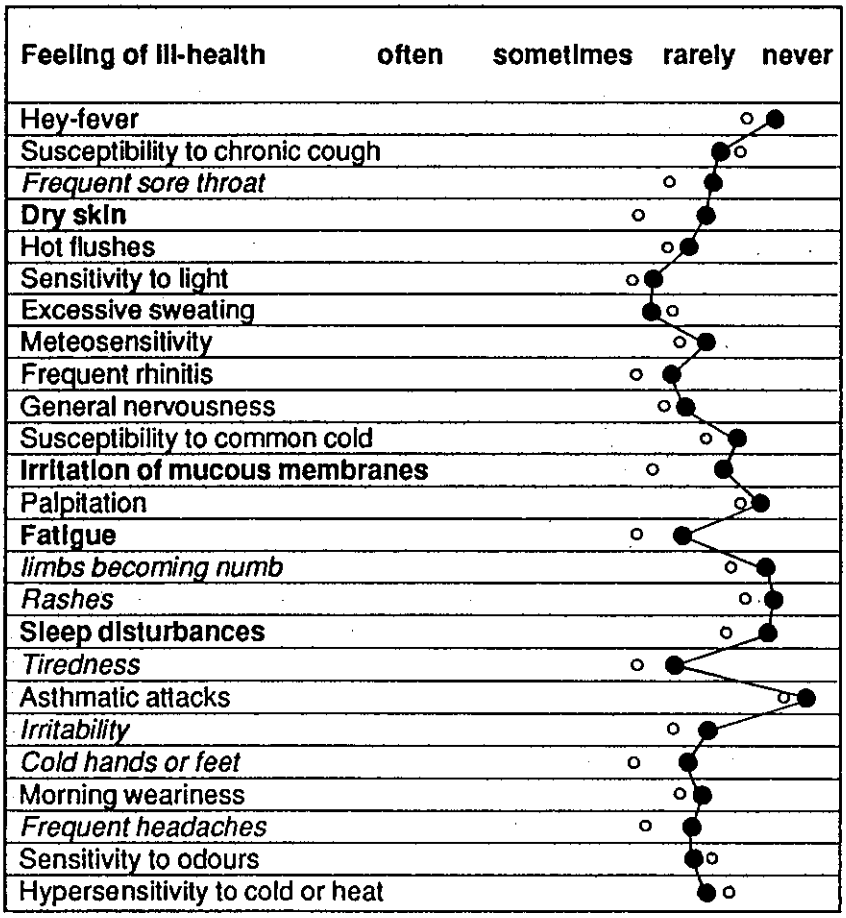


○ ○ ○ Air-conditioned area
●——● Atrium Pavilions

Significances: **bold** = p < .001
italic = p < .010

The results for the impressions of total space have broadly been confirmed (p= .060) and those for the impressions of working environment have significantly been confirmed (p= .016). Significant correlations could be stated concerning the lack of originality of total space and increasing health complaints of nervousness, common colds, and the lack of good mood. The impression of missing health in the working space and more serious complaints concerning nervousness, cardiovascular condition, and common cold also significantly correlate to bad mood.

Figure 32:
"Symptoms of Health Complaints"



○ ○ ○ Air-conditioned area
●——● Atrium Pavilions

Significances: **bold** = p < .001
italic = p < .010

- **Discussion of Monitoring Results**

The three presented studies (individual interviews, total interviews, and longitudinal section study) show that there is no significant difference between the conventional building and the atrium office pavilions concerning the impression of total space and the impression of close working space environment. Both spacial arrangements are perceived as multifunctional and equiped with good materials. Working space environments are perceived as quiet, handy, and comfortable. This fact seems logical since both the conventional office areas and the atrium office pavilions are characterized by an open plan office configuration. The great difference between the two office situations is characterized by their originalities and their atmospheres: In addition to the general advantages of modern open plan office concepts the atrium office pavilions enclose the vital originality and the inviting atmosphere.

The difference concerning the working spaces is mainly characterized by the evaluation of their quality for reasons of health: Working spaces of atrium offices additionally enclose aspects of health which are missed in the conventional office building caused by the air-conditioning system. For all studies investigating occupant satisfaction and user acceptance -and particularly in this case- the question arises, whether the positive results can be explained by the fact that employees have participated in an experiment.

This assumption was shown in the famous study about working conditions in the Howthorne factory of Western Electric Company and had become very wellknown by the "Howthorne Effect" (Homans 1952). However, in the case of the Tegut building in Fulda several factors exclude this kind of interpretation:

The Howthorne study investigated very different people using different dependent parameters within a different space. In Howthorne the interviewed persons were workers; in the atrium office in Fulda the persons are employees. In Howthorne the main aspect to be studied was the amount of telephone components produced by contracted piecework, in Fulda the objective included the impressions of office space and working environment. In Howthorne the experimental space was not an independent parameter but neutral; in Fulda the atrium with its intensive planting was an independent variable, and so on.

Moreover, the Tegut study was based on reiterative monitoring including relatively different staff configurations (only 7 persons have been working in the atrium for the total of the four interviews, 21 persons in the conventionally conditioned office area); the Howthorne study, however, was a longtitudinal section which could only be compared with the corresponding study of Tegut.

The stability of the two discriminating factors "originality of office space" and "healthy working space" under different conditions, provide a great validity considering the different space and a great reliability considering the different monitoring sequences. Thus, the interpretation of the "Howthorne - Effect" is not applicable.

Figure 33: View into the atrium from East. Photo: G. Löhnert

Figure 34: Pavilion light-weight roof construction. Photo: LOG ID

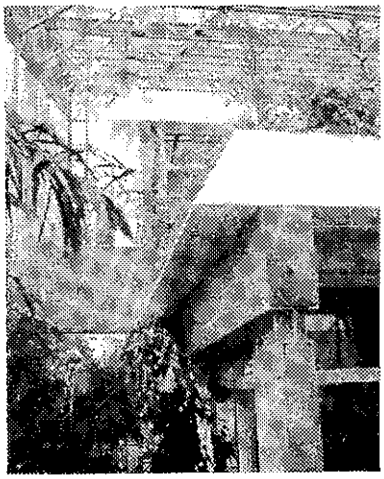


Figure 35: View from East to the office pavilions. Photo: G. Löhnert

III. CONCLUSION

Both the monitoring of energy performance and the investigation of users'acceptance have been supported in two separate projects by the Federal Ministry of Research and Technology. While the previous report focussed the most essential results according to these two investigations, a summarizing conclusion should now emphasize more extended evaluation in terms of hypothetic statements which may be relevant for future building designs.

It is the first time for the Green Solar Architecture concept that an evaluation of energy and amenity issues for commercial buildings has been carried out. Aside from the fact that the budget for occupant investigations do not meet the actual demand concerning number and magnitude of funding, the dual monitoring in this project shows that it was not possible to correlate results and tendencies from user acceptance directly with the "hard" data and parameters from the climate and energy related results.

For example, it is not possible to identify precisely if temporary exceedings of a specific climate indoor parameter at a certain time (i.e. temperature and/or humidity level) above human comfort standards will necessarily lead to a corresponding individual sensation of discomfort by the occupant. Adequate results addressing these correlations cause much more sophisticated monitoring and inquiry methods and tuning of monitoring plan. This approach should encouraged further research avtivities which include more medical, physiological, and psychological dimensions.

Relative to the building location (3451 degree days, global radiation 904 kWh/m^{2}a) the space heating demand of 144 kWh/m^{2}a and 187 kWh/m^{2}a including electricity is lower in comparison to conventional existing naturally ventilated office buildings (153 / 195 kWh/m^{2}a)* and much lower relative to those which are mechanically ventilated (181 / 250 kWh/m^{2}a)* or even fully conditioned (194 / 291 kWh/m^{2}a)*. Relative to future requirements upon new building energy performance of 70 kWh/m^{2}a* for heating the Tegut building energy demand is fairly big.

However, the evaluation of "usable space" should be discussed very carefully and is also relevant for almost each atrium building providing plant growth including temporal sedentary functions. In the study the utilisation of the terraces has been considered by an area- and comfort-weighted factor based on a thermal comfort range of 18°C - 28°C and an area of 71.3 m^2. These numbers could be modified for different reasons: On condition that intensive subtropical planting creates an attractive natural-like and pleasant atmosphere the occupants might use this environment even at air temperature conditions below 16°C and would also accept higher temperatures above 28° C as long as this particular environment would give a positive physical and psychological stimulation for the employees, and when people will adapt their clothing customs according to the thermal comfort fluctuations in the atrium. Moreover, the treatment of the usable area is a questionable limitation of a more complex spatial arrangement upon the actual accessable floor area. The spatial quality of the communication terraces is not

* The comparative energy figures have been taken from the Swiss SIA - documentation DO 24: "Energiekennzahlen von Gebäudegruppen"

(only) the net terrace floor area providing sedentary facilities for meetings and/or conferences. Much more, the quality is characterized by the amenity which is created by the spatial dimension, and the kind and overall appearance and greatness of the dense greenery providing visual and olfactory sensations towards the human physique and psyche. Thus, not only the enclosed accessable terrace floor area is relevant for the usability but also (at least part of) the attractive spatial scenery of the planting environment.

Consequently, these considerations would significantly affect the relation of specific energy demand for the existing Tegut building.

Moreover it should be mentioned that the atrium envelope consists of a standard double glazing as the client did not accept low-e glazing. It is obviously that a thermal improvement of the atrium envelope would decrease energy consumption drastically.

Most unfortunately parametric studies for building optimization providing valuable design guidelines for future projects have not been carried out. Nevertheless, the project has shown that it was possible to maintain the advantages of an open plan office and to improve its disadvantages which were caused by climatisation. The success shows that the principles of Green Solar Architecture may also be applied to buildings other than single family homes.

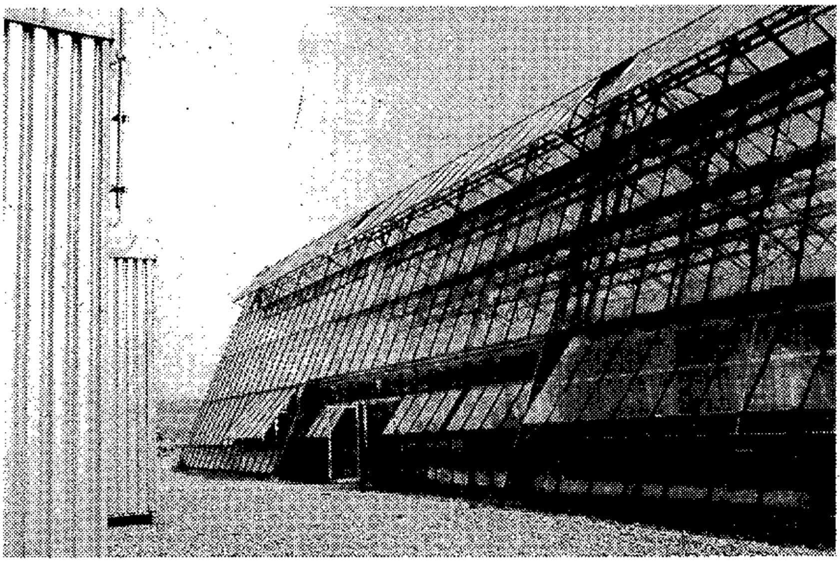


Figure 36: View to the West facade of the atrium taken from the roof of the existing old office building. Photo: LOG ID

INFORMATION

LOG ID: Grüne Solararchitektur, "Firma Tegut", a documentation of the building.

Prof. Dr. Gerd Hauser: Report about Investigations of Energy Performance, R+D Report Nr. 03 E 8574 A.

Prof. Dr. Martin Krampen: Final Report about Investigations of Users' Acceptance, R+D Report Nr. 03 E 8574 A.

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Evaluation of the ELA Building

NORWEGIAN INSTITUTE OF TECHNOLOGY
Extension to Department of Electrical Engineering and Computer Science

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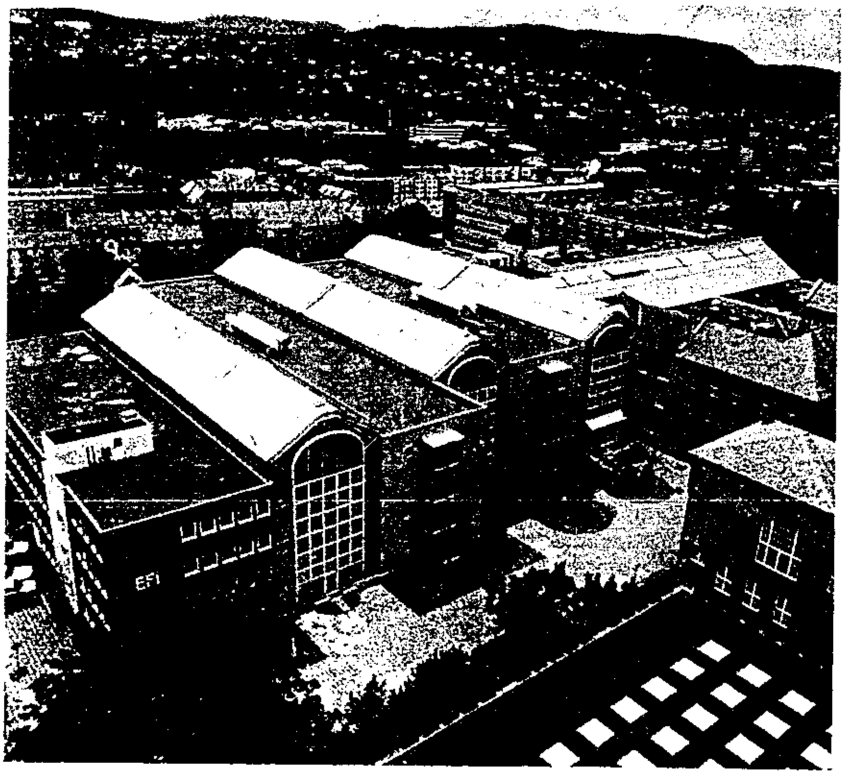


Fig. 1. The Department of Electrical Engineering and Computer Science at the Norwegian Institute of Technology, with the new extension (the ELA-building) in the center.

ACKNOWLEDGEMENT

This work was financed in part by the solar energy reasearch program of the Royal Norwegian Council for Scientific and Industrial Research. The IEA Task XI work relies heavily on results produced within the research program "Glazed spaces", which is also financed by Federation of Glass and Glazing Industry in Norway.

ABSTRACT

The extension to the Electrical Engineering Department at the Norwegian Institute of Technology in Trondheim, Norway, consists of several new office and laboratory buildings connected to each other and to existing buildings with glazed spaces. Preconstruction analysis indicated lower life cycle costs and reduced energy use, when compared to a reference without glazing.

The atria are heated by solar gains, by transmission losses from the surrounding buildings, and by some auxiliary heat to maintain a minimum +15C design winter temperature. This set point has later been raised to about +18C, allowing for more extensive occupancy by students of the atria spaces. The energy use has been monitored for 1 1/2 years; the results are close to the projected values, and very low compared to similar buildings and recommendations.

The buildings received favourable comments from the occupants in surveys. There are complaints about uncomfortable conditions in office spaces facing the atria. This is caused by overheating in the upper parts of the atria during sunny periods and no possibility for window venting to cooler surroundings. The fire ventilation hatches provide sufficient venting in the summer to keep temperatures down, but they are not operated properly at all times.

Simulation studies compared to detailed measurements during stratification conditions, show that a one-zone model will not give satisfactory results for such conditions. Daylight factor measurements agree quite well with modelled results for the atrium floor.

A postconstruction cost analysis with actual contract prices show that the investments were somewhat lower for the glazed alternative, due to simpler construction of the facades facing the atria.This more than paid for the atria glazing.

1.INTRODUCTION

The design team for the extension to the Electrical Engineering Department at the Norwegian Institute of Technology had earlier collaborated in the design of two other major glazed spaces buildings in Trondheim.One of these was the new University Center at Dragvold in Trondheim. In this new building they wanted to explore the experiences gained earlier by incorporating semi-conditioned atria for student and faculty circulation and other temporary occupancy.

The client, the Directorate for Public Construction, had to be convinced that this was a cost-effective solution, and consequently the design team undertook a series of preconstruction analyses of energy use, temperature conditions, and cost, partly in cooperation with the research institutions at the Technical Campus.

After occupancy, postconstruction analyses and evaluations were performed within the framework of the Trondheim Group for Glazed Spaces. In most respects, the preconstruction results proved to be reliable. In addition, valuable experiences with thermal comfort issues, ventilation, and daylighting were gained during the evaluation of the building.

2.BUILDING DESCRIPTION

The extension project includes offices for faculty and researchers, smaller seminar rooms and exercise labs, light electronics and computer labs, a multistorey high voltage lab, and a cafeteria. New auditoria were also built, by reconstruction of existing lab facilities.

The extension consists of three new parallel four storey rectangular blocks and four linear shaped atria, filling out the spaces between these and existing buildings. Three of the atria are on an E/W axis with glazed gables, while the fourth atrium fills out the space between two existing N/S axis buildings, one of which includes the new auditoria.The new office blocks are approximately 12*50 m in plan, (4 storeys + basement) and the linear atria about 10 m.wide, see fig. 2 next page.

The buildings are located on the campus plateau of the Norwegian Institute of Technology in Trondheim, Norway, at latitude 63.5N and elevation 50m. The west facade of the new extension has an unobstructed horizon, otherwise the building complex is surrounded by buildings of approximately the same height.

Some climate data for Trondheim:

Heating season degree days, base +20C:	4180Cd
Annual average temperature:	+4.9C
Design temperature, heating power:	-19.0C
Annual global horisontal radiation:	815 kWh/m2
Heating season global horisontal rad.:	220 "

The new buildings are constructed of precast concrete columns, beams, and hollow core slabs, with steel frames as structural support for the atrium glazing.The exterior walls are insulated concrete sandwich panels, with double glazed low-E windows. The intermediate walls facing the atria have infill insulated woodframe panels, with single glazed windows. The atrium glazing is double low-E, laminated overhead.

The U-values are:

Atrium glazing:	2.1 W/m2*K
Exterior windows:	2.1 "
Intermediate walls: (incl. windows)	3.2 "

The buildings are heated by hot water radiators supplied from a central plant which is now connected to the city's district heating system. The atria have convector heaters at several heights along the glazed gables and a radiant heat strip along the overhead ridge (see fig.3).

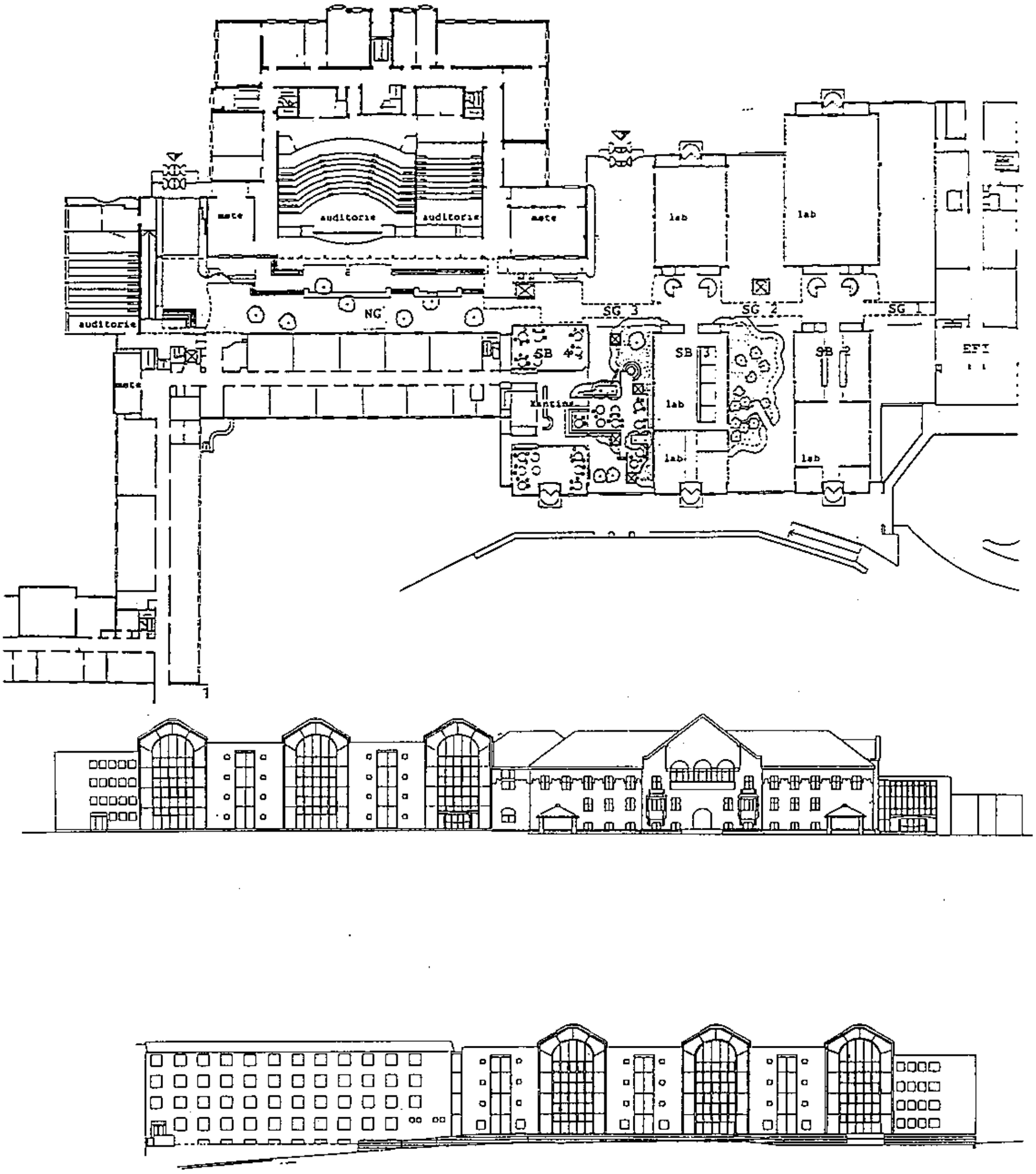


Fig. 2. Ground level plan and elevations for the new building complex.

The buildings have balanced mechanical ventilation, while the atria depend solely on infiltration. Some of the fire ventilation hatches in the gables and the glazed roofs are used for summertime venting. All service ducts etc are placed within the atria along the facades and are thus easily accessible for alterations and maintenance.

The atria are heated in the winter period to a design minimum of +15C, by passive gains through the glazing, by heat losses from the surrounding buildings, and by auxiliary heating. This atria temperature was selected after detailed preconstruction analysis and simulations. The heat transmission losses from the surrounding buildings, which are kept at 20C, are consequently very small, giving an overall heat loss which is smaller than for the same complex without atria.

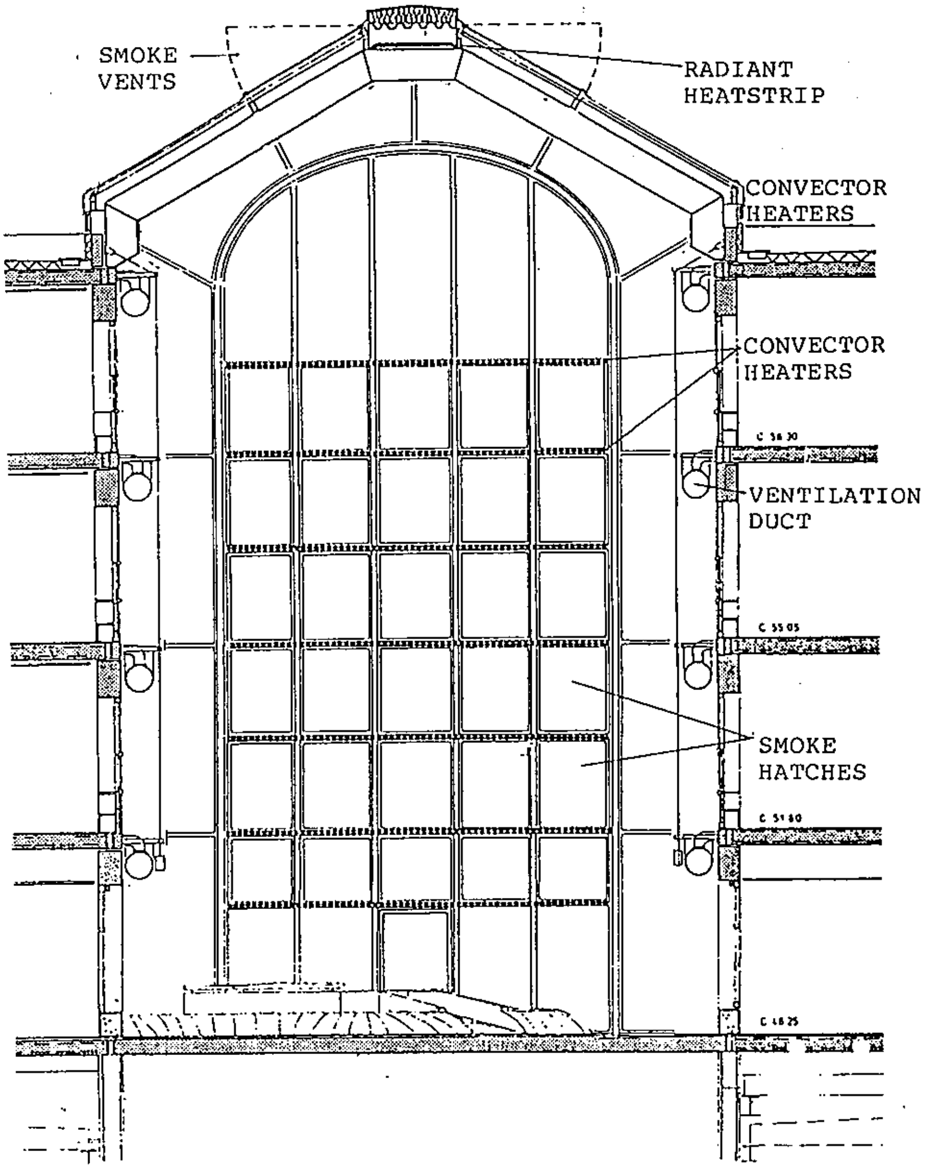


Fig.3. Cross section and gable wall of atrium with heating and venting systems.

3.EVALUATION LEVELS

The objectives of the different evaluations efforts undertaken for this building project are:

to test the preconstruction analysis results
to analyze certain features in the atrium design
to provide data for evaluation of computer programs
to test user reaction conclusions reached earlier in similar projects
to gather general information about the performance of this type of buildings
to generalize the evaluation data into design tools for designers.

In terms of the evaluation levels defined for the IEA advanced case studies, the objectives and hypotheses of the postconstruction evaluation projects are, in general terms:

1. Compact building complexes with infill of semiconditioned glazed spaces as daylight sources have a potential of both total energy and cost savings, and favourable user response.

2. The atria themselves will provide attractive spaces for circulation, informal meetings, work or lecture breaks etc for the building occupants, while maintaining comfort in the fully conditioned ordinary buildings. The minimum ventilation in the atria in the winter period provided by infiltration is adequate, and summer venting through smoke ventilation is sufficient to keep temperatures down to acceptable levels.

3. The new buildings compare favourably to other buildings of the same category and generation, in terms of energy use, cost, and amenity.

4. By collecting detailed data for the major feature of these buildings, the atria, we will be able to provide other designers with information and design tools that will enable them to ensure even better performance in future buildings.

5. Special features of the atria can be successfully modelled in simulation programs by using the data collected for this project.

Since the atria are the special passive features of this project, most of the analysis objectives in levels 1-3 have been to compare the building to a reference building without atria, and with the facades towards the glazed spaces constructed as the other exterior walls in the new buildings.

4.MEASUREMENTS

4.1 Energy

The objectives of the energy measurements and related temperature and infiltration measurements, were to find answers to these questions:

> Do the measured energy use match the preconstruction calculated numbers, which were the basis for the decision to set the atria heating to +15C?
>
> Are the atria and building temperature levels in agreement with the design set points?
>
> Can the atrium temperatures be successfully modelled with a one-zone simulation model?

The heating energy and the energy used for lighting, equipment etc was monitored on a weekly basis for one office block and one atrium for the period Nov. 1987 to June 1989. In addition, the total heating demand for the whole complex was measured. Weekly maximum and minimum temperatures were registered both in an atrium and in an office block, at different levels. These weekly data are plotted in fig. 4 and 5 below.

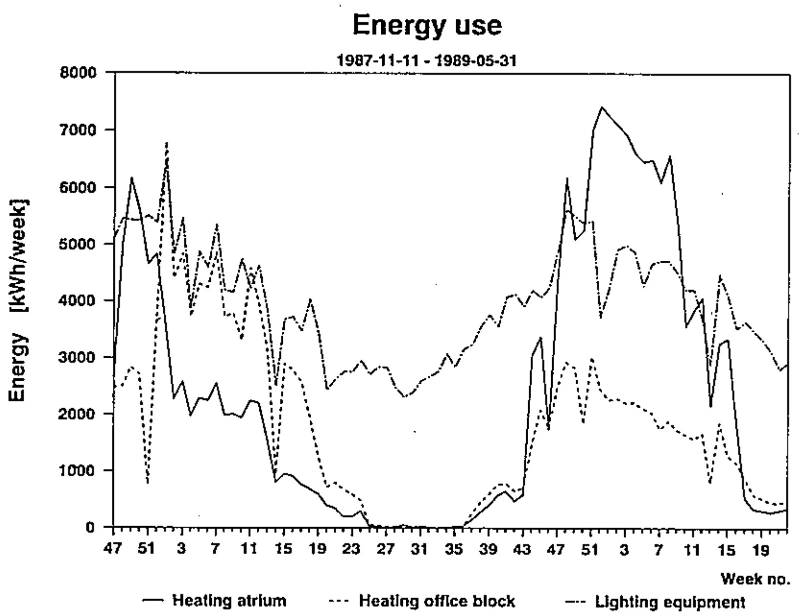


Fig.4. Weekly registrations of energy use in one atrium (535 m2) and one office block (2665 m2) during the measurement period.

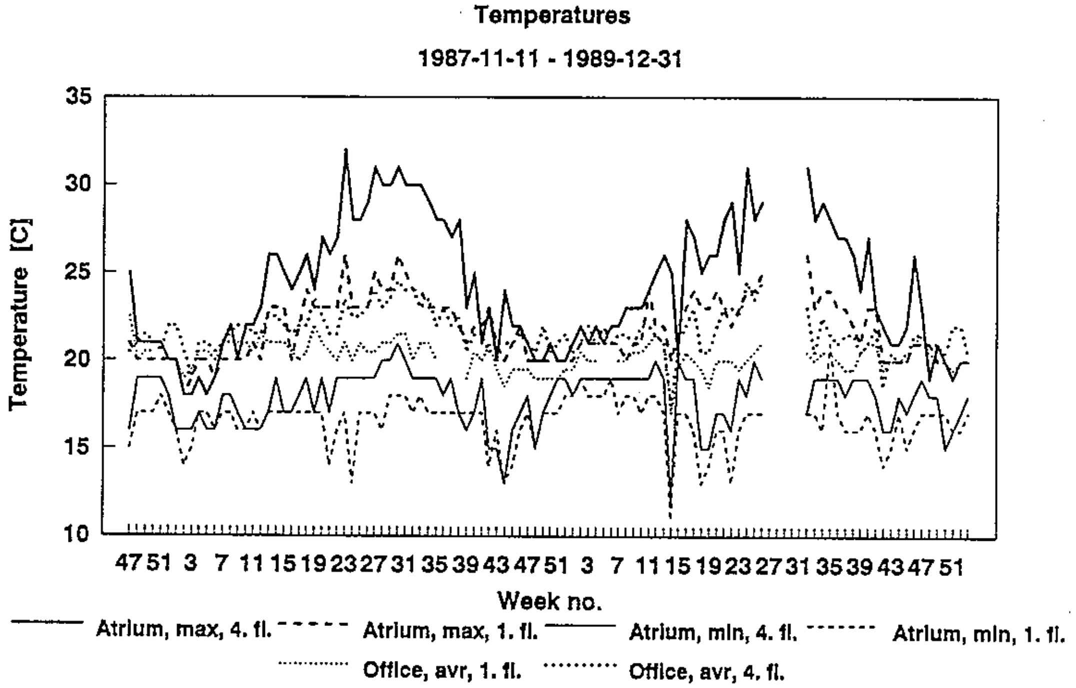


Fig.5. Weekly temperature registrations at 1. and 4. floor level in one atrium and one office block. For the office block the average of weekly maximum and minimum is plotted.

Detailed temperature measurements were also carried out in one atrium during a short period of the 1988 summer. This was done to study the stratification process and to supply measurement data for simulation studies.

Some energy results are given below:

Office block, lights, equipment	67	kWh/m2*yr
Office block, heating	41	"
Atrium, heating	148	"
Office block + atrium, heating	60	"
Whole complex, heating	65	"
Total energy use:		
Office block + atrium, measured	127	"
Office block + atrium, precalc.	124	"

Comparison numbers:

Norwegian universities, average	270	"

Energy budgets according to NS 3032:

New offices:	Low	90	"
	Average	110	"
	High	130	"
New laboratories:	Low	150	"
	Average	200	"
	High	250	"

The numbers show that the new buildings compare well with other university buildings and recommended energy budgets. The total energy is also remarkbly close to the projected design figure. This may, of course, be just a coincidence, but the precalculations are now being checked in detail.

The temperature registrations, however, show that the temperature in the atrium has risen steadily since the building was occupied, from a design +15C to +18C in the last heating season, as a result of user de- mands. The atrium spaces were intended to be used for circulation and temporary occupancy during lecture breaks etc. only, but because of the general over-population of students in the complex, they now use them as general study places, which require a higher temperature for thermal comfort.

Consequently, the atria heating demand has also risen steadily in the period, fig. 6, while the office heating energy is somewhat reduced, as the transmission losses to the atria now are almost zero.

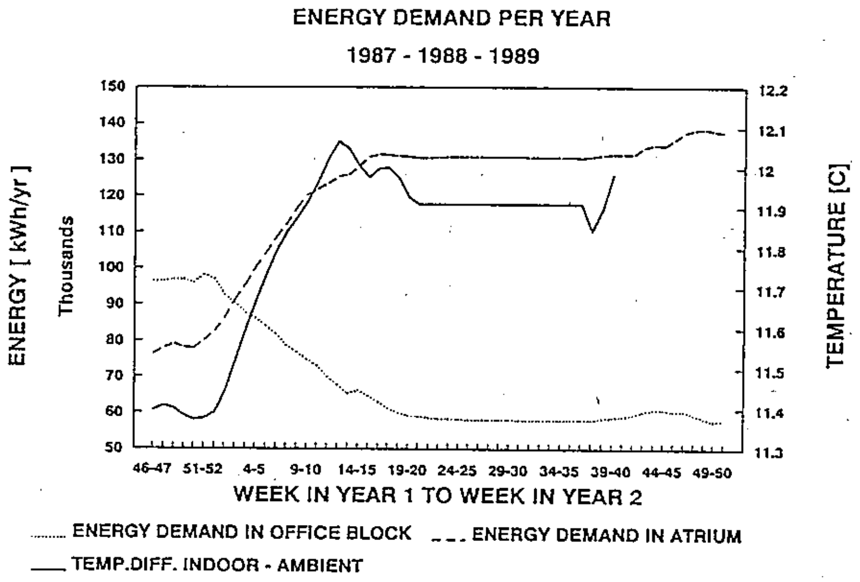


Fig.6. Trends in the annual heating demand in one office block and one atrium over the measurement period depending on selected measuring period.

4.2 Amenity

The amenity issues related to this building project are:

Do the atria provide sufficient thermal comfort for the activities intended?

Do the fully conditioned spaces surrounding the atria provide adequate thermal comfort and air quality, or has the presence of the atria any effect on the comfort level here?

Is the infiltration sufficient as ventilation for the atria in the winter period?

Is the venting through smoke ventilation hatches adequate as summer cooling of the atria?

How do the occupants react to having windows only facing the atria?

Are the daylight levels in the atria and in the surrounding buildings adequate?

How are occupant reactions in this building compared to reactions in similar buildings?

How do amenity issues in the final building compare to considerations at the design stage?

In order to answer these questions, the measurements reported in sections 4.3 - 4.5 were carried out.

4.3 Thermal climate

Rather detailed measurements of thermal climate were conducted during one winter period, 1987-03-10-- 1987-03-17, and during one summer period, 1987-06-22 --1987-08-18.

In the winter period the ambient temperature was in the range of -11C - +4C; the cloud conditions were very variable. The observations made during the period can be summarized in the following:

- There was no need for venting by using the hatches.
- The atrium neede auxiliary heating at night only.
- The air temperature in the lower part of the atrium varied between the night-time low of 15C and the day-time high of 21C.
- The temperature gradient between floor level and 2.5 m never exceeded 1C.
- Maximum temperature in the upper part was 32C, at the same time the temperature in the lower part was 19C. Even on overcast days the temperature in the upper regions was above 23C.
- In the evening the temperature in the upper part quickly fell to 16 - 18C.
- The temperature difference between the top and bottom level was 1 - 2C during the night.

The summer period included both normal weather conditions and one week of extremely good weather. The latter had an ambient temperature cycle of between 15 and 24C, with clear skies. The normal weather period had a daily average temperature of 14C and changing cloud cover. The observations made during the period can be summarized in the following:

- The air temperature in the lower part of the atrium varied between 18 - 28C, depending on the ambient temperature, solar radiation, and open venting area. There was no overheating problem.
- The temperature in the upper part was 2 - 3C higher than in the lower part of the atrium. This created an overheating problem in the offices facing the atrium at the upper level - there was no point in window venting for these offices.
- The average temperature in the atrium did not rise during a week of successive warm and sunny days.
- There was very strong temperature stratification when the hatches were closed during the period of good weather. The temperature in lower part rose just 2C above the venting case, but the maximum temperature in the upper part increased 14 - 16C (see fig.7).

Air temperatures in the office blocks reach uncomfortable levels during sunny periods in the summer, because the venting through the smoke hatches is not always used when required. The operation of the hatches is on manual control by the building operator, and unless uncomfortable situations are reported, he may not know that there is a need for venting. Automatic control is now being installed. Also, the consequence of loosing the possibility for window venting, may not be sufficiently taken into account.

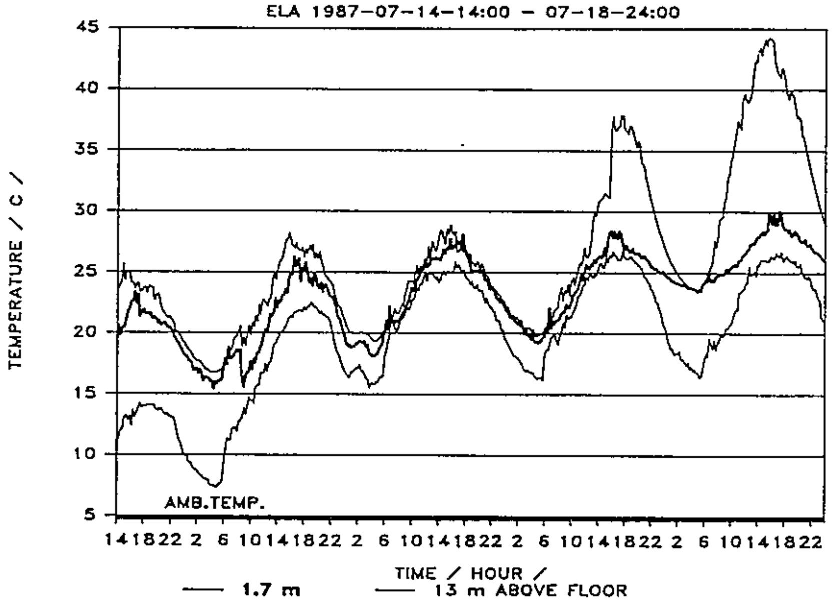


Fig.7. Air temperatures in the atrium at two levels during a warm sunny period in July. The hatches were in the open venting mode the first 3 days and then closed.

4.4 Air quality, ventilation

The ventilation air volumes in the offices were checked by some measurements and found to be only one third of the design values. The system was then rebuilt and adjusted to correct volumes (-7.5m3/h*m2 floor area, with inlet temperature of 16C).

The air change rate was measured in one atrium with a step-down tracer gas method and mixing fans. The test was performed in July, with an indoor/outdoor temperature difference of 10 - 13C, and a wind speed of 1 - 3 m/s. This test, and several other tests, show an air change rate per hour of 0.45 - 0.50, indicating that infiltration gives an adequate ventilation rate. But under winter conditions, when typical temperature differences are in the 20C region, the atrium may be too leaky.

With the hatches in normal venting position, typical air change rates were 3 - 4 per hour, but it should be emphasized that these measurements were rather inaccurate, as the mixing fan capacity was inadequate.

Some measurements were also carried out without mixing fans, in order to trace the air flow patterns in the atrium with hatches closed. These showed that the lower part of the atrium had the cleanest air, and that the upper part functioned as an air outlet; an air flow pattern similar to displacement ventilation.

One concern that should be addressed, regarding air change measurements in further work, is infiltration and exfiltration to the neighbouring office blocks. Smoke tests indicated some exfiltration into upper floors of the oldest block with badly sealed windows. The pressure differences also indicate some infiltration from the lower floors of the blocks.

4.5 Daylight

One-time measurements of daylight factors were carried out in one atrium, using a recording reference instrument on the roof of a nearby unobstructed building and handheld illumination meters in the atrium. Some spot checks were also carried out in offices facing the atrium. However, due to some instruments uncertainties the results are not conclusive and more measurements have to be done.

The preliminary results are indicated in fig.10 (p.18). Along the centerline of the atrium floor, the daylight factors were from 17-19% close to the east gable wall and fell gradually to around 12-14% in the vicinity of the elevator and staircase shaft. On the walls facing the atrium, values were in the 7-9% range at heights of 1.4 to 2.2 meters above the floor.

Spot checks in some offices facing this atrium showed daylight factors of 2-3% on first floor level, 3-4% on second floor, and 3-5% on third floor, all measured on horisontal work tables app. 0.7 m above the floor and app. 1.1 m from the window wall plane.

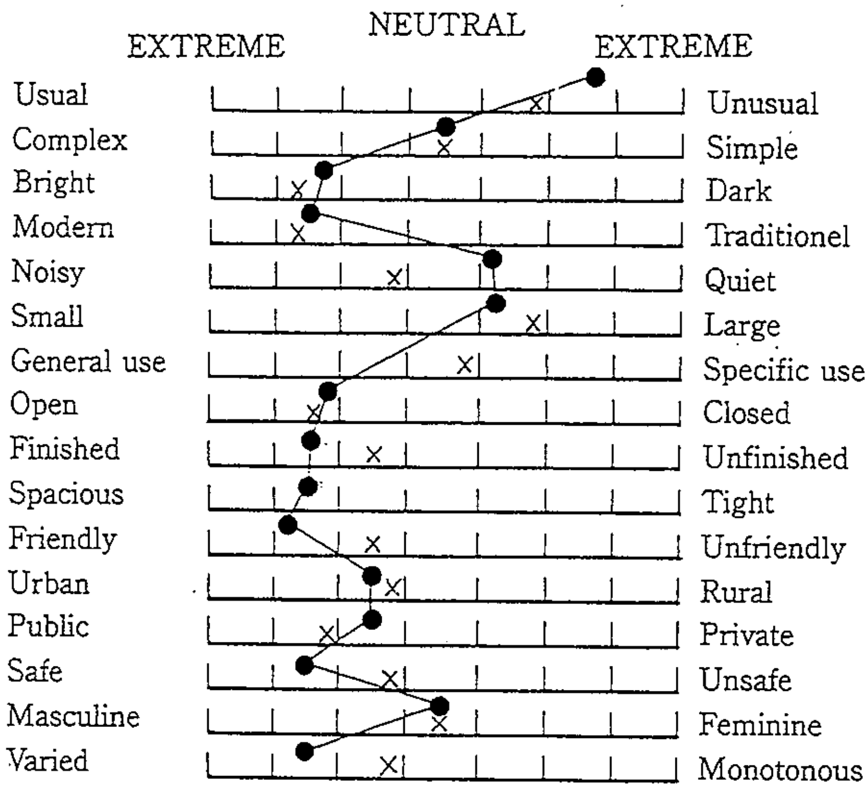
4.6 Occupant opinions

The occupants' reactions to thermal comfort, air quality, and daylighting were also tested in a comprehensive survey, using a questionnaire based on similar work done by University of Wales. A linear rating form used earlier in the evaluation of the similar university building in Trondheim, the Dragvold University Center, was also included. The main survey was performed i August 1988, with a follow-up, on winter issues only, in December.

Some major conclusions are:

- There are many complaints about high temperatures and poor air quality in offices facing the atria. This is probably related to the fact that in sunny periods the air temperature in the atria is above comfort levels, so there is no help in opening windows. The complaints are not correlated to floor level or orientation, but the existing buildings have more complaints than new, because of poorer mechanical ventilation systems.
- Occupants are on the whole satisfied with conditions in the atria themselves.
- Daylight levels are considered adequate, but artificial lighting is kept on all year.

- The rating, on linear attribute scales, is quite similar to the rating given the University Center glazed street (see fig.9 below).
- Noise levels in the atria and noise disturbance from the atria to the office spaces also give rise to some complaints.



x ELA
o Dragvold

Fig.8. Occupants' rating of the ELA building and the Dragvold University Center on linear 7 point attribute scales.

4.7 Costs

During the design phase, a cost study was performed in order to convince the client that is was economically feasible to glaze the spaces between the buildings instead of leaving them open. This study was updated after construction with actual contracting prices and as-built data. The construction and operating costs of one atrium with surrounding offices were compared to an open reference alternative. Only costs that differed for the two cases were studied, and the cost figures for the un-built reference was calculated with statistical cost data from the same period. Life cycle cost were calculated for a real rate of interest of 7%, according to public investment policy, with depreciation periods of 50 years for structure and 20 years for service systems.

The major investment cost differences for the glazed alternative were:

- Cheaper facade walls because of simpler construction, single glazing etc.
- Smaller total facade wall area because structure was left exposed and uninsulated.
- The added cost of the glazed roof and gables, with structure, services, controls etc.
- Cheaper ventilation ductwork because of easy, uninsulated ducting along facades.
- Higher cost for increased heating power because of atrium auxiliary heating.

The only operating cost that differs for the two alternatives is the energy cost, which is calculated to be 20% lower for the glazed alternative, the analysis performed before measured data were available.

Investments proved in sum to be lower for the glazed case, in the order of 2-3% of total construction costs. The cost of glazing is more than offset by the savings associated with the facade walls towards the atrium, proving that the overall geometry is the key parameter. The break-even point for this case was 4 storey buildings with a glazed street of 10m width between.

Total lifecycle savings per floor area was in the order of 20% of the cleaning cost.

Not accounted for in this cost study was the value of the atrium floor space and the reduction in the number of staircases and elevators.

The method used in this study is now being generalized with a standard accounting system and data base added. The intent is to provide designers of atrium buildings with a better, standardized tool for cost analysis.

5.SIMULATIONS

5.1 Energy and temperatures

The main objectives of the energy simulation studies performed for this building, were:

to check the accuracy of the preconstruction analysis
to check the accuracy of a one-zone model in the case of strong stratification in the atria
to do parameter studies of different alternative designs.

The simulation model used in the postconstruction analysis was TARP, Thermal Analysis Research Program, developed at National Bureau of Standards. In the preconstruction analysis the consultant's own program was used, together with the multizone model ROYAL-DEBAC.

The measurements show reasonably good agreement with precalculated and design values, both for temperatures and energy use. The monitoring method, using manual registration of recording instruments, seemed to give the necessary level of detail for the objective of finding out if the building works as intended.

The agreement between precalculated (124 kwh/m2 year) and measured (127 kwh/m2 year) energy use may be coincidental. A more detailed analysis is now undertaken in order to establish more information on why this happened, and in order to evaluate alternative designs.

Certain measurements from the ELA-atrium, both in winter and summer, have been compared to simulations run with the TARP program. Figure 5 presents the measured temperatures at different levels and the simulation results for one day in July. The simulated temperature is close to the average temperature in the upper part of the atrium both in magnitude and phase, but it does not provide any information about the thermal climate at floor level. Periods with little stratification give rather good agreement between measurements and simulations, i.e. night and winter periods.

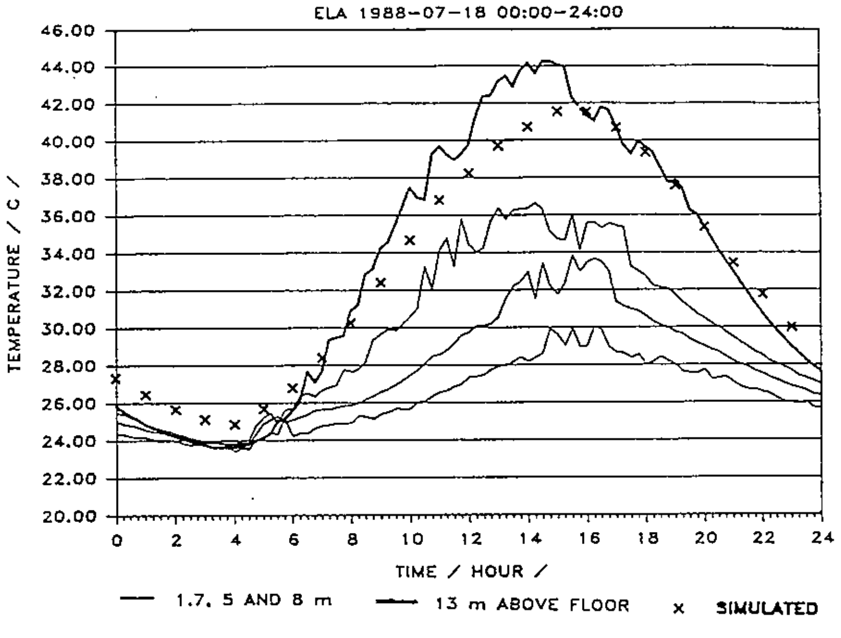


Fig.9. Measured air temperatures at different levels compared to simulations with TARP. The venting hatches were closed in this case.

5.2 Daylighting

The daylight factor levels in one atrium were calculated, using the computer model SUPERLITE 1.0, provided by Lawrence Berkeley Laboratory. The objective of this work was:

to gain experience with the model
to find out if it was suitable for this type of building
to find out if the numbers it yields would correlate reasonably well with measurements.

Since both modelling and measuring in this case was rather limited, our work cannot be termed a real validation effort.

Superlite was used to find daylight factors in approximately the same points as were measured earlier. Both CIE overcast and uniform sky were calculated, giving quite similar results. This is not surprising since the atrium was receiving daylight only from a narrow strip of zenith sky. The CIE sky gave about 10% higher values than the uniform sky.

The real case was rather complicated to model, as the atrium has large obstructions in the center caused by a staircase/elevator shaft and gangways between the two office building facing the atrium. Only the east wing of the atrium was measured, as the other end is heavily obstructed by greenery. Reflectances of atrium surfaces were measured with a luminance meter and standard grey cards. For glazing transmission product data was used, with an "educated guess" correction for obstruction caused by structure, glazing bars etc. Obstruction by nearby buildings on the east side was also modelled.

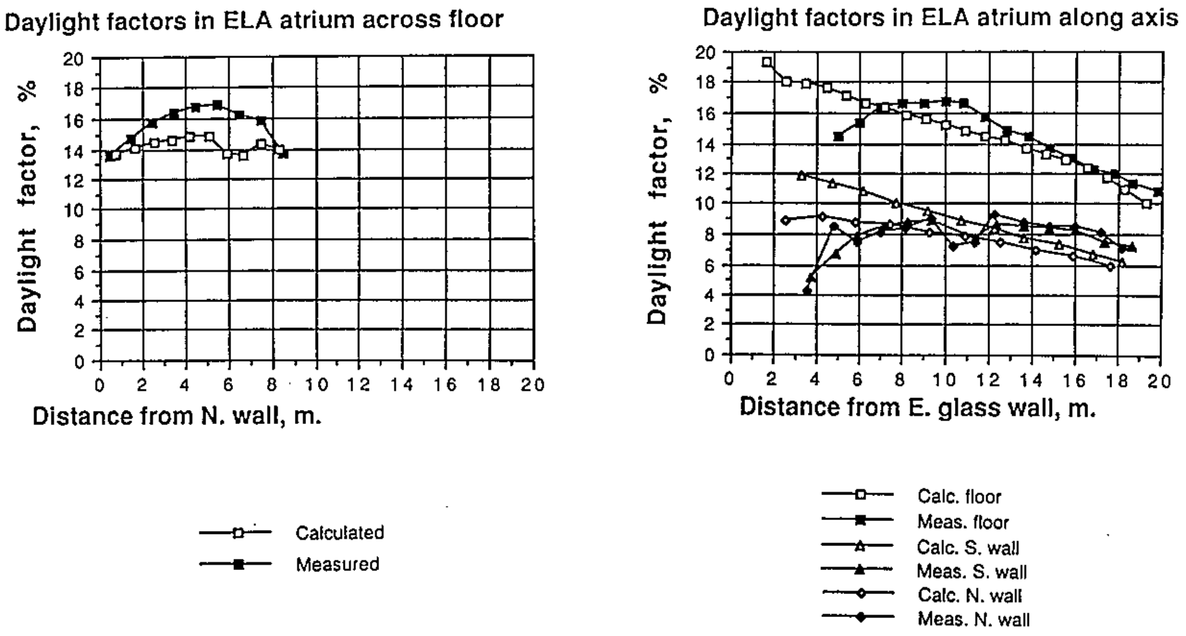


Fig.10. Calculated and measured daylight factors in the east half part of one atrium, for points on the floor and on the walls at window height for the ground floor.

Calculated results are shown in fig.10, which also indicates some measured results for reference. The good agreement between the two sets of values and coincidence in general trend is surprising, considering the limitations of the program and the complexity of the real case and the many details that could not be modelled properly, and the uncertainties in the measured results.

6.CONCLUSIONS

The major conclusions drawn from this case study are in short:

The measurements show reasonably good agreement with precalculated and design values, both for temperatures and energy use. The monitoring method, using manual registration of recording instruments, seemed to give the necessary detail level for the objective of finding out if the building works as intended.

Temperature and ventilation measurements also agree well with user reactions.

The agreement between precalculated and measured energy use may be coincidental. A more detailed analysis is now undertaken in order to establish more information on why this happened.

Measurement of energy use and temperatures also in general agree well with simulations performed. The same applies to daylight factor levels. However, in sunny periods the atria temperatures show strong stratification, which is not modelled properly with a one-zone simulation program.

The energy use in the new complex is low, compared to other buildings of same category and generation. The energy use is also in the low end range of the recommended budget figures for this type of building.

The atria heating set point has been steadily rising since monitoring started, due to more demanding activities there now than originally intended for these spaces. Consequently, heating demand for the atria has increased, while heating in the office blocks has been reduced, but to a lesser degree than the atria increase. The heating load in the office spaces, with very little transmission losses and high internal gains from computers, lighting etc, is now so small that electric heating should be more cost-effective than the installed water radiator system.

The infiltration of fresh air to the atria, about 0.5ACH, seems to give satisfactory air quality. When open, the fire ventilation hatches give sufficient venting to keep the summer temperatures at acceptable levels. However, the vents are on manual control and not always opened when required. This gives rise to many complaints about uncomfortable temperatures and poor air quality in the offices facing the atria during sunny periods. Due to stratification, the atria temperatures at higher levels prevent window venting.

The occupants judged the daylight levels to be sufficient, both in the atria and in the adjoining office spaces. However, the artificial lighting is left on during all working hours. On other amenity issues, there seems to be general satisfaction. The building complex received a rating on linear attribute scales, that was quite similar to the rating of another university building in Trondheim with glazed streets.

Cost analysis show that this building complex have lower investments and energy costs than a reference alternative without glazing. The savings attributed to a simpler exterior wall facing the atria more than offset the cost of the overhead and gable glazing and structure. This makes the main geometry, the street heigth to width ratio, the key cost parameter.

7.RECOMMENDATIONS

The evaluation of this building proves that the designers' original intentions have been met: a cost-effective and energy-saving university building with high amenity value in this type of climate. However, there are quite a few lessons to be learned that have the potential of ensuring more succesful buildings of this type in the future.

First of all, it is important to establish a use of atrium spaces that makes it possible to operate this type of spaces at an intermediate temperature, compared to the surrounding fully conditioned buildings. Otherwise, these buildings can easily become energy wasters.

The heating set point for the atrium spaces do not, however, need to be set so low as to impair comfort for many important building functions, such as circulation, short breaks, lobby, etc. The optimum atrium temperature should be found by careful analysis of energy use and costs, taking different geometries, intermediate facade construction and atrium glazing into consideration.

The main geometry, atrium height to width, is the governing parameter for both energy balance, costs and daylight conditions.

During sunny periods, stratification will give temperatures above comfort level at the higher levels in the atria. This can only be properly modelled with a multi-zone simulation model. This type of condition can lead to uncomfortable conditions in the spaces facing the atria. It is important to ensure that vents will be properly used, or alternatively, shading or other systems that could prevent the stratification should be included.

Having work spaces that face a glazed atrium is quite acceptable, but it is important to incorporate solar shading and sufficient ventilation or cooling to maintain thermal comfort. Otherwise, a general negative attitude towards the building will develop.

With reasonable heating season temperatures maintained in the atria, the transmission losses from adjacent buildings will be almost negligable. Most of the heating load here will be covered by internal gains from occupants, lighting and equipment.

Simulation models that can handle the energy balance and daylight conditions in atrium buildings seem to need some further development.

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N DAY CARE CENTER Advanced Case Study

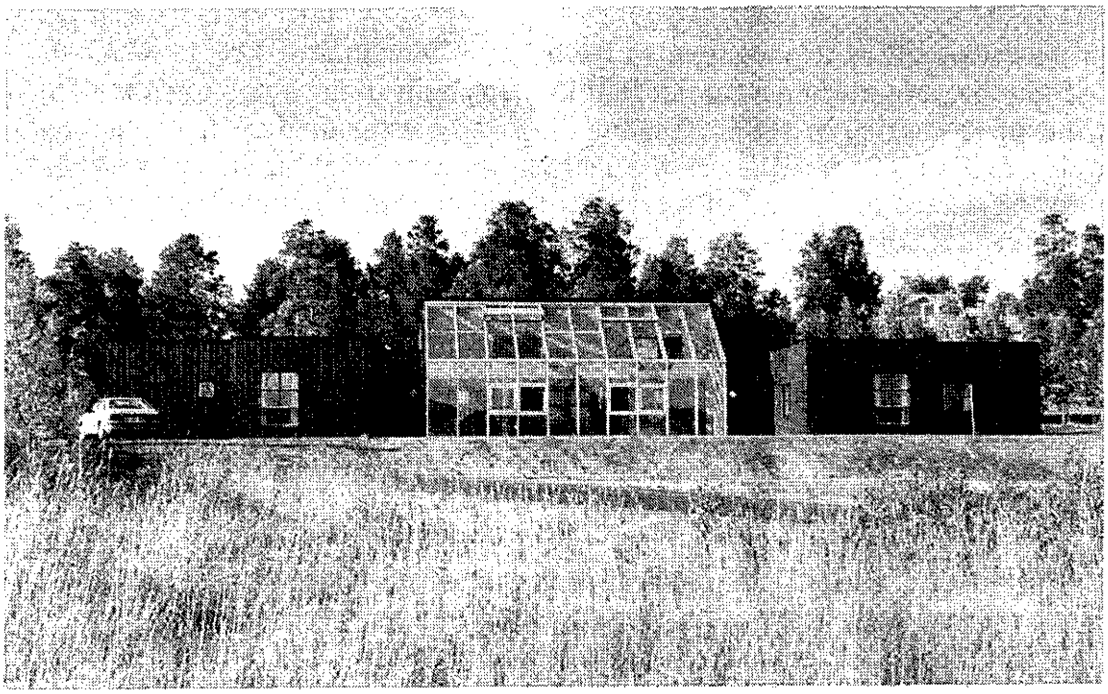

Figure 1 View from south

Authors : I.Bryn, A.G.Hestnes

ABSTRACT

This building is a day care center where the main solar feature is a large, centrally located sunspace that acts as a preheater of ventilation air. The glazed space was expected to reduce the energy consumption in the rest of the building and at the same time provide an additional space for the children.

The prototype was built in Alta in 1987. It was monitored in 1989. At the same time the users were interviewed. To investigate alternative solutions, simulations were performed with realistic data on internal gain.

The building is not built as initially planned. The floor heating system has no thermostat, and there is no maximum control of the temperature on the ventilation air from the atrium. This has caused high energy use and discomfort because of high temperatures. Frequent use of equipment such as washing machines and dryers has also influenced the energy use.

The atrium provides a place where children enjoy playing and physical activity. The employees would prefer a higher temperature in the atrium to increase the use of the atrium. An alternative and better solution would be to separate the ventilation and the heating systems. Heat pump in connection with the atrium should be considered.

1 INTRODUCTION

The day care center was planned as a prototype to be built in Trondheim. The project was delayed due to lack of funding. Meanwhile a similar building was built in the small town of Alta in northern Norway during the spring of 1987. This building was not planned as an evaluation object. Due to the delay in Trondheim, Alta was then chosen as the evaluation object and the planning of the monitoring started at the end of the construction period. The monitored project is a part of the Norwegian Ministry of Oil and Energy's prototype programme.
Its purpose is to investigate both the energy savings and the amenity value of such glazed spaces in day care centers.

2 BUILDING DESCRIPTION

2.1 FORM AND CONSTRUCTION

The building is planned for four identical groups of children, two on each side of a central zone. This zone contains a service area with offices, a common kitchen, etc. to the north and the glazed space to the south. All the entries are located in this semiclimatized zone, which also serves as a link between the different groups.

As the building is only used in the daytime, and not on weekends and vacations, a low mass building was chosen. The building is constructed in wood. Insulation levels are relatively high, with 150 mm mineral wool in the exterior walls, 250 mm in the ceiling, and triple glazing. The glazed space has a laminated wood structure with aluminum profiles and double glazing.

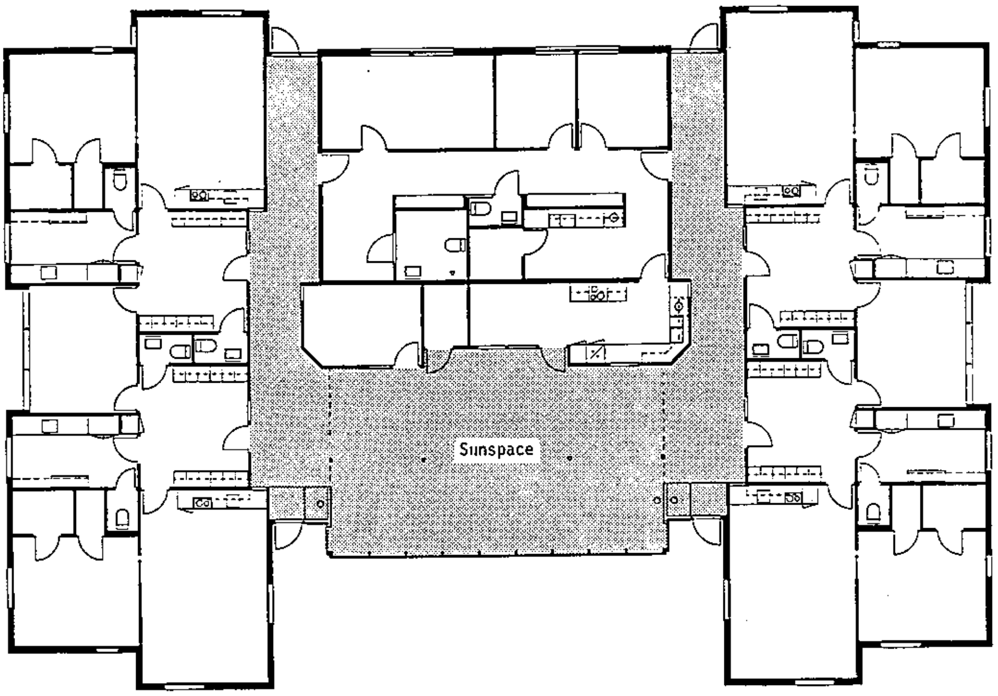

Figure 2 Plan

Building form data:

Volume	m^3
Gross:	1275
Semiclimatized:	259

Glazing areas:	m^2
Exterior heated zone:	22
Exterior semiclimatized:	65
Interior:	21

Glass area is 18 % of facade viewed from the inside. Glass area is the same in all directions.

Thermal data:

U-values	W/m^2K
Floor:	0.15
Walls:	0.26
Windows:	2.00
Atrium windows:	3.00
Roof:	0.15

Heat loss W/K	Transmission	Infiltration
Heated to ambient:	255	82
Heated to atrium:	117	
Atrium to ambient:	219	40

Thermal transfer ratio:
$U^*A_{atr\text{-}amb}/U^*A_{atr\text{-}heat}$: 1.83

Volume ratio:
Atrium/total enclosed space: 0.19

2.2 PASSIVE SYSTEMS

The semiclimatized, glazed space reduces the energy consumption in the rest of the building by acting as a buffer zone and thus reducing the heat loss. The heat gained in the space is in addition used to heat the rest of the building. This is done by supplying all the fresh air to the building via the glazed space and thus obtaining a certain preheating effect.

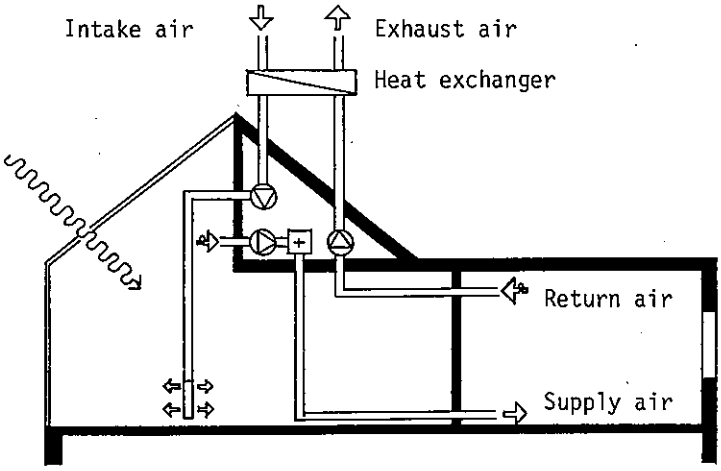

Figure 3 Air flow diagram.

2.3 SITE AND LOCATION

The building is located on a relatively flat site in a residential area outside town. The site is protected on the north side by a small forest, while it has full exposure to the sun on the east, south, and west sides. South of the building the site also slopes slightly downwards.

Site data:		
	Latitude:	69.6 N
	Altitude:	80 m

Climate data:

Degree days, base 20°C	
October-May (incl)	5092
Annual	6600
1989	6139
1978 (year of simulation)	7391

Temperatures	°C
Average annual	1.7
Average 1989	3.0
Design winter	-22.0

Solar radiation	
Global annual radiation,MJ/m^2	2391
Annual sun hours	1606
Actual/theoretical sun hours	0.5

2.4 BUILDING SERVICES

The basic heating system is electric radiant floor heat. This is supplemented by electrical space heaters located under the windows. Only the space heaters have temperature control. The ventilation system passes air through a heat exchanger and into the glazed space. The air is then heated up to 20°C and distributed diffusely to the rest of the building. The building and atrium is vented through hatches when the temperature is too high. The ventilation system is only operated when the center is in use.

Design temperatures	°C
Heated space	21
Atrium	floating

Ventilation	
Air change, m^3/h	2250
Heat exchanger efficiency,%	80

3 MEASUREMENTS

3.1 QUESTIONS AND HYPOTHESES

The objective of this project is to answer hypotheses about the energy use, cost, indoor climate and amenity values of the building. Following are the hypotheses to be answered:

Energy:

E1) The building has high energy performance.
E2) The building uses less energy than others.
E3) The building would work better if surplus heat from the atrium could be used directly in the heating system.

Indoor climate:

C1) The atrium temperature is 10 - 15 °C above ambient.
C2) The climate in the atrium is best in spring and autumn.

Amenity value:

A1) The building has high amenity value.
A2) The atrium provides a good climate for playing.
A3) The atrium increases the amenity value of this building relative to others.
A4) The atrium is best in spring and autumn, but it also works well as a shelter in wintertime.

3.2 METHODS

3.2.1 Monitoring

Hourly average values, sampling every 10 min.

Energy, power to:
1) Ventilation system
2) Light, hot water, dryers.
3) Equipment such as dishwashing and washing machine, stove.
4) Heating.

In addition weekly manual registration of total energy consumption.

Temperatures:
1) Three levels in atrium 1.5, 3, 5 m.
2) Global temperature in atrium.
3) In kitchen.
4) Before and after heat exchanger.
5) Room on north side.

Climate data:

Global radiation.
Diffuse radiation.
Wind.
Ambient temperature.
Comparisons with recordings from the Norwegian Institute of Meteorology for control and supplement.

3.2.2 Questionnaires

The users have answered a questionnaire twice about the indoor climate, use of equipment, comfort and how they enjoy the building. A questionnaire about energy use and comfort is sent to the other day care centers in Alta. Planning and building costs are obtained from the building owner.

4 FINDINGS

4.1 ENERGY

Total energy use in 1989 was 107 720 kWh. The part that can be used for heating is 88900 Kwh. This is 50 % higher than expected. The distribution of monitored energy use is shown in table I. Total energy use is 263 kWh/m^2 related to heated area. This is higher than in other day care centers in the area. Energy use is shown in table I.

Table I Energy use. Monitored.

Energy use (Kwh)	Total	Usable as heat	Not for heat
Hot water	6094	0	6094
Light, drying	18346	18346	0
Stove, drying	15080	7540	7540
Ventilation	9300	4200	5100
Heating	58900	58900	0
Total	107720	88986	18734

The precalculations were performed for the year 1978. Degree days have been used to compare the precalculations and the monitored energy use. This is shown in table II.

Table II Energy use. Calculated and monitored.

	Calculated, REF	Calculated	Monitored
Year:	1978	Corr to 1989	1989
Degree days:	7391	6139	6139
Equipment	30637	30637	30086
Heating	34496	23463	58900
Total	65133	54099	88986

Reasons for high energy consumption:

1) Floor heating has no thermostat. This causes overheating in periods.

2) The surplus heat from atrium is not used since the floor heating don't have a thermostat. The warm air from the atrium causes overheating in periods.

3) Overheating occur almost daily. The users of the building vent manually two hours every day.

4) Doors between the atrium and rest of the building are often open.

5) Atrium temperature is higher than calculated.

6) The day care center is highly equipped, with many washing machines and dryers.

The hypotheses about energy consumption was:

E1) The building has high energy performance.
E2) The building uses less energy than others.
E3) The building would work better if surplus heat from the atrium could be used directly in the heating system.

The monitoring shows that this building has low energy performance and use more energy than others which give a negative answer to hypotheses E1) and E2). Our new hypothesis, referred to as E4, is that the problems listed above is the reason for this, and that a correction of this would give the building the expected energy performance. Hypotheses E3 and E4 is studied in the simulation section.

4.2 INDOOR CLIMATE

The hypotheses about indoor climate are:

C1) The atrium temperature is 10 - 15°C above ambient.
C2) The climate in the atrium is best in spring and autumn.

Hypothesis C1:
Monitored atrium temperatures are shown together with ambient temperature in figure 4. The atrium temperature lies 15 to 25 °C above ambient. The atrium temperature falls below 10°C 2% of the time, and the minimum temperature is 6°C. It is to be compared with an atrium which is heated to between 10 and 15°C. Precalculation showed that the temperature would be below 10°C 35 % of time and that the minimum would be -10°C. The high atrium temperature causes low energy use by the ventilation system, but it seems as the atrium is unnecessary heated.

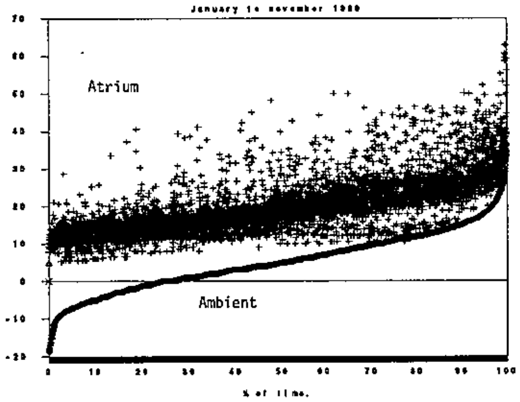

Figure 4 Ambient temperature sorted in ascending order together with corresponding atrium temperature.

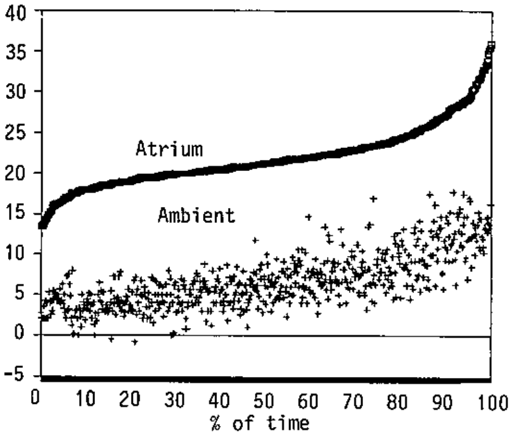

Figure 5 Atrium temperature in May sorted in ascending order together with corresponding ambient temperature.

Hypothesis C2:
Figure 5 shows that the atrium temperature in May is 15°C above ambient temperature most of the time. Monitoring also shows tat no heating were used in the atrium. We find that the atrium offers a good climate in the spring. The same is presumed for the autumn. The conclusion is that hypothesis C2 is correct.

The monitoring shows a temperature difference between floor and ceiling levels (5 m) is 4 to 8 °C.

The users of the building complain about the air quality and temperature in the heated part of the building. The atrium is normally felt as refreshing and with good air quality.

4.3 AMENITY VALUES

The day care center is used by 48 children and 15 adults. The building provides 7.8 m^2/person. The working hours is from 08:00 to 16:00 monday to friday. The main idea behind the project is to provide additional space for the children to play in. The atrium is used as an alternative to the heated area, not especially when it is cold or wet outside. It is used for play activities similar to those indoor such as singing, "training" etc. Two handicapped children use it when it is too cold outside. They also test green plants in the atrium for a horticultural college.
The users wish to increase the atrium temperature in order to use it for other activities.
We find that all the hypotheses about the atrium amenity value is correct.

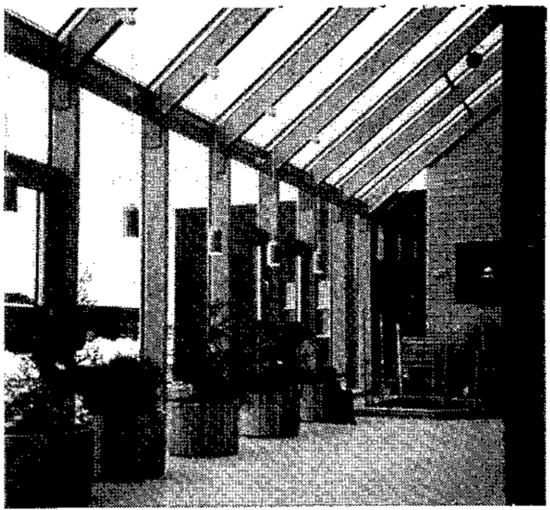
Figure 6 Interior view.

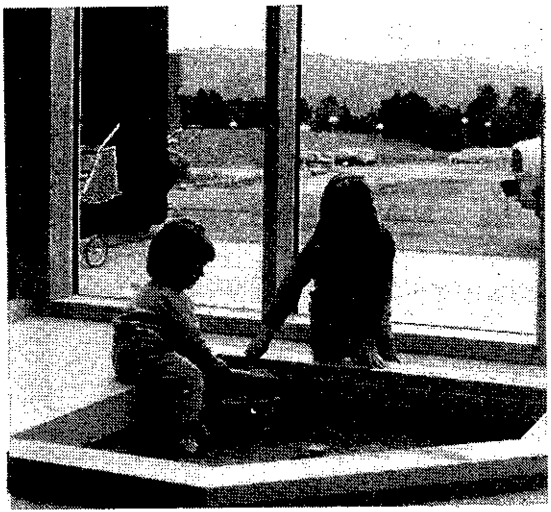
Figure 7 Interior view.

4.4 COSTS

Preconstruction calculations show that the energy savings potential is not quite high enough to make the system cost effective. Glazing systems on the market are too costly, and the energy price too low. When taking the amenity value into account the total cost is considered acceptable. The total costs of the atrium itself, excluding all mechanical equipment, was NOK 250 000. Both the price of the atrium and of rest of the building is quite representative. The high energy consumption result in running cost for the building. Installation of thermostats and reduction of atrium temperatures are cost effective.

Building costs (1987):	7800 NOK/m^2 gross 1026 ECU/m^2 gross
Atrium cost (1987):	3125 NOK/m^2
Fuel cost(1989),Electricity:	0.33 NOK/kWh

5 SIMULATIONS

5.1 OBJECTIVE

The objective of the simulations was to investigate the sensitivity of important building parameters and to find the reason for the higher energy use of the building than expected. Following are the parameters to be investigated:

A) Variation of the glazed area in the atrium.
B) Variation of U-value of the glazed area in the atrium.
C) Variation of intermediate area of atrium and heated part of the building.
D) Variation of atrium temperature.
E) Simulation of "as is".

F) Simulation with only ventilation of heated zone.
G) Simulation of a situation where a heat pump is used to enhance the utilisation of heat gain from the atrium.

5.2 MODEL AND ASSUMPTIONS

The simulation model FRES was used. The model is described in the Atrium part of the Source book.
The building is subdivided into two zones, the atrium and the heated part.
Internal gains to heated area from persons are: 8350 kWh and from equipment: 21149 kwh. Internal gains to atrium from equipment are 6435 kWh.

5.3 FINDINGS

Simulations A to D.

Figure 8, 9 and 10 show the results of A) to D).

The sensitivity of the glazed area in atrium, and between atrium and heated area, is low.
A triple glazed window in the atrium glazing to the ambience would reduce the energy consumption, but it is not economical. Triple glazing should be considered with a higher atrium temperature.

Heating of the atrium above 5°C increases the heat consumption remarkably.

Simulation E
To simulate the "as is" situation several assumptions had to be made. These are:

1) Double infiltration, 0.4 ach/h to simulate open windows.
2) 22°C indoor temperature, increased from 21°C because of poor control of heating system.
3) Open doors between atrium and heated zone.
4) Heat exchanger efficiency 0.6
5) Heating of atrium to 12°C.

The result shows an energy consumption for heating of 57867 kWh, and total 88504 kWh.
Correction by degree days to 1989 values gives a total consumption of 78700 kWh compared to the monitored total value, 88986 kWh, shown in table II, fourth column.
The conclusion is that hypothesis E4 is right and that the system as a principle works well. The reason for the high energy consumption lies in the poor control of the heating and ventilation system and the increased atrium temperature.

Simulation F
Ventilation only of heated zone gave a minor reduction of energy consumption.

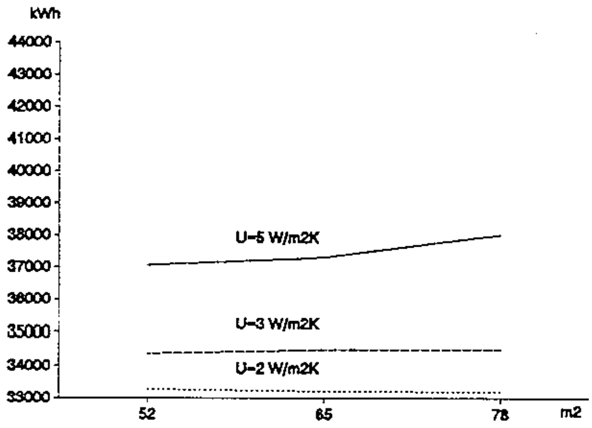

Figure 8 Heat consumption. Variation of U-value and area in the glazed part of the atrium.

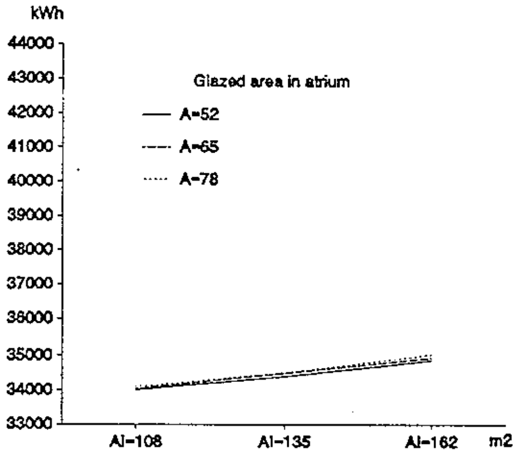

Figure 9 Heat consumption as a function of intermediate area. Variation of glazed area in atrium.

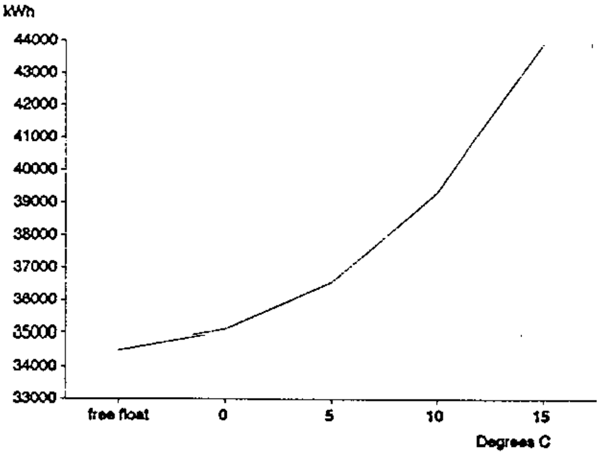

Figure 10 Heat consumption as a function of atrium temperature.

Simulation G
A heat pump, which utilizes exhaust air from the atrium and the building, is studied to test hypothesis E3. The heat pump may be a source both for space heating and hot water heating. Thus surplus heat in the summer is used for hot water heating. The system makes it possible to reduce the total energy consumption for heating by an extra 10000 kWh compared to the reference case (Table II, first column). The economics of this solution should be studied.

6 CONCLUSIONS

The main idea of the building is achieved, as it provides additional place for the children to play. It is felt pleasant and refreshing to be in the atrium.

Both the heat consumption and the atrium temperature is higher than precalculated. This is caused by poor temperature control and heating of atrium. A reduction of atrium temperature together with temperature control in the heated area will reduce the energy consumption. A control of the temperature in the heated area will also increase the thermal comfort and reduce the need for manual venting. The system as a principle works well.

7 RECOMMENDATIONS

7.1 IMPROVEMENTS OF THE BUILT SYSTEM

- Control of floor heating system in sequence with space heaters. The floor heating should be as low as possible, while the space heaters should be used for temperature control.

- Control of maximum air temperature by control of ventilation air inlet without bypassing heat exchanger.

- Reduced energy consumption for ventilation equipment by changing motors.

7.2 IMPROVEMENTS OF THE SYSTEM AS A PRINCIPLE

- Heating and ventilation should be two separate systems.

- A separate system, ie a heat pump should take care of surplus heat from the atrium, and deliver it to space or hot water heating.

- The building and heating system should have a quick response.
  Radiators give quicker response than floor heating.

8 INFORMATION

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Advanced Case Study

THE "BODBETJÄNTEN" PROJECT IN STOCKHOLM, SWEDEN

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SUMMARY

The building contains north-facing offices and east-, west, south-facing apartments plus two atria. The main experimental energy principles are two:

1) Surplus heat from offices is transported by the exhaust ventilation air partly through the atria, partly through ducts in the concrete slabs of the apartments.

2) The atria act as buffer zones and for passive solar gains.

A heat pump and short time thermal storages are also included.

Results from extensive measurements on a high monitory level and their evaluation are presentated and discussed.

1 INTRODUCTION

Emphasis of project

In the Bodbetjänten development, a system is being tested whereby surplus heat from offices can be used to heat residential parts of the same block and also to heat hot water.

An orientation of the building with residential apartments facing south and offices facing north means that solar heating will benefit the residential section in the first instance. Moreover, there will be less need for cooling in the office section.

A large glazed courtyard, or atrium, that borders towards the south and towards the residential sections serves as a passive solar collector. Vertical glass surfaces enable heat from the sun to benefit the building during times when the sun is low. At the same time, an insulated roof ensures low heat emission during hours of darkness.

Air from the office section circulates via prefabricated hollow- core slabs in the apartment flooring. It is assumed that the air in the offices has a higher temperature than the air in the apartments. For the greater part of the year, some of the office air is circulated through the glazed courtyards, which are partly heated in this way while it also cools the offices. The temperature in the courtyards was expected to be at lowest +15 °C during the day and +8 °C during the night.

Heat is conveyed to the building with heat-pump technology. A heat pump is used to recover heat from comfort cooling of the office section. The heat pump is also used to recover heat from the ventilation air from the apartments and parts of the offices. In certain operating cases, the courtyard serves as an active solar collector. Surplus heat from the courtyard is then restored to the heating and hot water system of the building via the heat pump.

Water accumulators are used to store surplus energy. An electric boiler has been installed for peak heat load supply.

Summary of what was learned

Despite the technical preconditions for transport of heat, the actual transmission of heat within the building has been limited. There are two main reasons for this. For one thing the need of cooling, i.e. available surplus heat, has been less than anticipated in the calculations, and for another the differences in temperature between different parts of the building have often been too small for transport of the designed amounts of heat.

The location of the offices, north of the residential section and with windows largely facing north, has resulted in a substantial decrease in the need for cooling. The location of the offices in a northern aspect, and the possibility of "night cooling" has reduced the amount of available surplus heat that could have been supplied to the dwellings or the atrium.

When surplus heat has been available, the possibilities of transmitting this via the hollow-core floor slabs were limited by an unanticipated high temperature level in the dwellings, resulting in small temperature differences between the offices and the dwellings. The temperature in the residential apartments has been lower than that in the offices only for short periods of time.

Measured atrium temperatures have been appreciably higher than anticipated.

The function of the glazed courtyard as a cooler for the offices has been reduced in that the courtyard was heated more than anticipated. The unforeseen increments of heat consist primarily of loss heat from the substation adjacent to the courtyard, the atrium lighting and heat from fanwork.

The function of the atrium as a solar collector has also been negatively affected by the courtyard being heated more than anticipated. The ability to supply solar energy to the courtyard is proportional to the differences between the temperatures in the glazed courtyard and outdoors.

In simulation calculations, the need of total purchased energy has been estimated at approx. 81 kWh/m2 total heated area. During 1987 electrical energy equivalent to 129 kWh/m2 (BRA) and year was purchased.

The deviation is mainly due to the following:

- the outdoor temperature during the measurement year was lower than during the "simulation year".
- the energy contribution from the experimental measures was smaller than calculated
- the use of building electricity was higher than calculated
- the COP of the heat pump was lower than calculated.

The total amount of purchased energy for both residential apartments and offices is nevertheless small in comparison with the averages for equivalent Swedish building production during the 1980s.

The main reasons for this are:

- the contribution from the heat pump
- effective commissioning
- a well adapted control and regulating system
- the buffer function of the glazed atrium and its ability to utilize loss heat from the substation
- main lay-out in relation to compass point and use
- recirculation of office air via the glazed courtyard.

2 BUILDING DESCRIPTION

Location, form and function

The Bodbetjänten development is situated on an unshaded site in the southern Stockholm suburb of Gubbängen. It comprises a residential block that is built together with an office block. The building contains 41 residential apartments and 3000 m^2 of office space.

The residential apartments and office premises surround a glazed courtyard which is divided by means of a glass partition between the office section and the residential section. Both the residential and the office parts of the building are four stories high. The offices are accessed via a stairway in the courtyard and via internal corridors. The apartments are accessed by stairways and balconies within the glazed atrium.

Building construction

The foundation slab consists of on-site-cast concrete with an underlying insulation layer of 50 mm styrene cellular plastic. The structure consists of prefabricated concrete facade, pillars and floor elements. The floor elements are hollow-core slabs, the ducts in which are used for air transport and heat accumulation in accordance with the so-called TermoDeck principle. The partition wall between the atria is glazed and steel framed.

The exterior walls consist of prefabricated concrete elements provided with cast-on mineral wool insulation. The facades are clad in brick. The wall facing the courtyard has a higher U- value than the outer facade - 0.35 and 0.27 W/m2K, respectively. The roof is covered with plate. The roof insulation consists of 240 mm mineral wool. The windows in exterior walls have triple glazing (2+1 panes, U=1.8). Double-glazed, sealed panes are used in windows facing the courtyard (U=2.8 W/m^2K).

Building services

In the heating system a continuously working heat pump (32/90 kW) takes heat from:

- heat exchanger of residential and office exhaust air (all year)
- heat exchanger of residential atrium circulating ventilation loop (sunny winter days)
- heat exchanger of office supply air (summer).

The heat pump loads heating water storage tanks. The stored heat is used (through heat exchangers) for:

- domestic hot tap water production
- office supply air heating when needed
- convector heating in apartments.

The heat pump capacity alone covers the needs most of the year. As back-up an immersion heater (115 kW) is installed. Draught from office windows (at ambient temperatures below +3 °C) is eliminated by electric resistance heaters.

The office ventilation system interacts with the duct loading of residential floor slabs. During office hours in winter supply air is planned to be mixed with recirculated air through the atria. During summer outdoor supply air is heat exchanged with the heat pump when needed.

The office atrium is ventilated by fans and automatically opening vents. The apartment supply air is taken in through slit valves behind convectors under windows. Exhaust air is fan operated and heat exchanged to heat pump circuit all year. In the residential atrium a slight excess in air pressure is kept to counteract leakages from outside and from apartments. On sunny winter days an air circulation fan feeds a heat exchanger in the heat pump system. In summer, when needed, the atrium is cross ventilated.

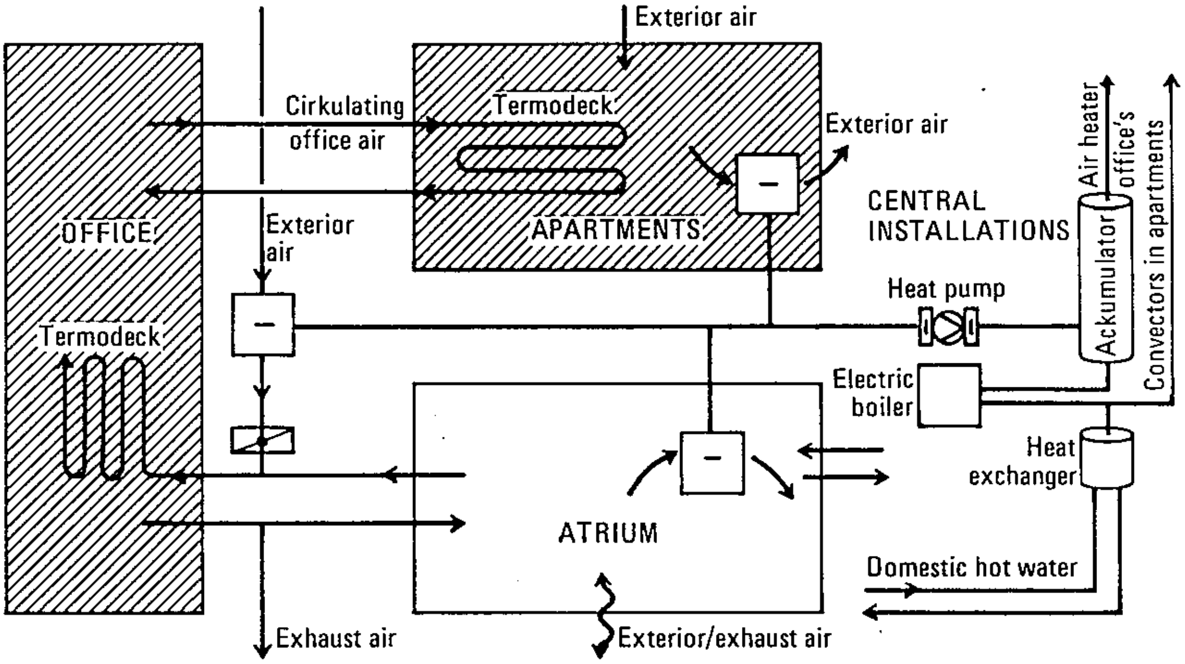


Fig.1 The principles for the heating and ventilation system in the building.

Solar features

The atria act as buffer zones and passive solar collectors. The heat storage in the apartment floor slabs by office exhaust air may also be looked upon as a passive hybrid device. See detailed building services description above.

All atria glazed parts are vertical, whereas the atria roofs are opaque and insulated.

The building is oriented so that the office part is facing north and the residential parts facing south, east and west. Such an orientation ensures that no overheating problems are encountered during the summer, and that the south-facing residential premises have the full advantage of sunshine throughout the year.

The operating modes of the atria heating system are:

- Winter time - the return air fan is started and air warmed by the sun is passed through a heat exchanger.
- Summer time - the atrium is ventilated by opening vents in the roof and the south facade. During non office hours the air in the atrium may be cooled.

3 MEASUREMENTS

Questions

The purpose of the evaluation is to obtain a picture, with the aid of dependable measurements, of how energy is used in the Bodbetjänten block and on the basis thereof to evaluate the energy technology experiments. Use in this context relates to both supplied and removed energy and to how the energy is transported and utilized in the various parts of the building. Supplied energy includes "purchased energy" for heating, water heating and electricity for households and building services.

Since the goal of this research project has been to decrease the use of purchased energy one of the main goals of the evaluation is to determine this use and to find explanations for deviations from the calculations made in advance.

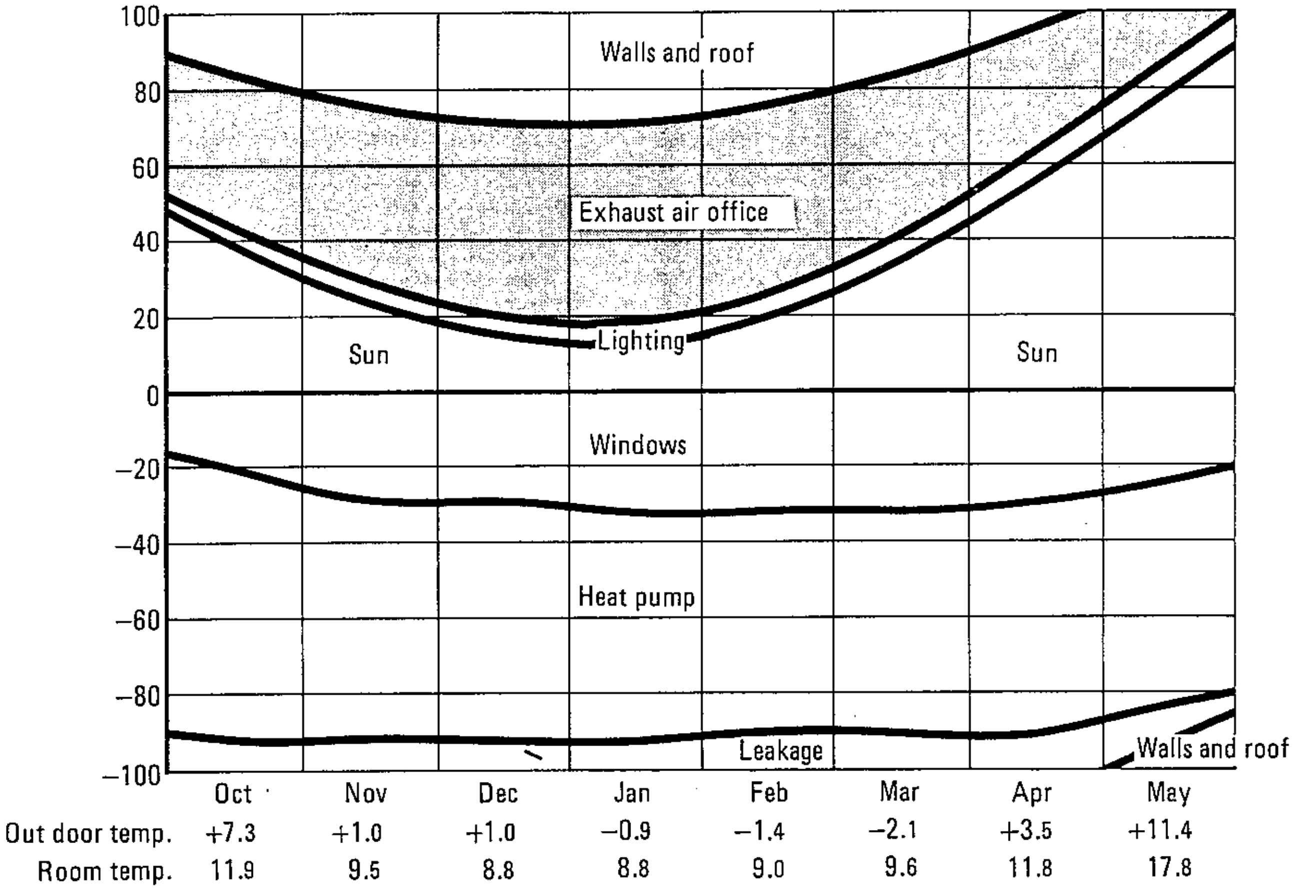


Fig.2 Envisaged/calculated energy balance in the atrium in per cent, and temperatures in the atrium and outdoors.

Once it is known how energy is used in different parts of the building it is possible to calculate how much purchased energy is used in the offices and how much in the residential apartments. This is of significance when making comparisons between Bodbetjänten and other buildings. Moreover, it is possible to assess the energy contributions related to the experimental actions.

Another object of the evaluation is to study the contributions from the different energy conserving measures and to determine if these compete. This may involve reduction of the aggregate effect of several measures that are effective in themselves. For instance, the calculated surplus heat from the offices may decrease owing to cooling of the offices during the night with cold outdoor air.

The results and experiences should be applicable to new and conversion activities, primarily with regard to similar solutions. Although the Bodbetjänten block consists of both residential apartments and offices it is hoped that the evaluation will prove to be valuable in more oridinary contexts.

Methods

Because the building comprises very different use of patterns it is necessary to describe not only the total supplied energy but also the energy flows within the system. From the standpoint of energy technology the various parts of the building differ considerably from one another with regard to temperature, air change rates, hours of occupation etc. Knowledge of the manner in which the supplied energy is used and transported between the different parts of the building before being discharged is thus important.

Purchased energy is divided into eight sub-items on the basis of the measurements made. The allocation of purchased energy for heating and hot water production in the offices and residential apartments respectively is not directly measurable. The two parts are therefore calculated on the basis of how the offices and dwellings respectively make use of the heat produced in the boiler and heat pump.

The results for the offices are presented as monthly sums and annual summaries for total purchased energy. (See figure 4.)

The atria are parts of the recycling system by way of reducing the transmission losses and feeding the heat pump. With knowledge of energy flows to and from the atria, the recovery function of the latter can be sought for. The ratio between recovered/free energy and supplied purchased energy for the atrium has been studied.

The function of the atria as climate buffers is determined by calculate hours of the amount of solar heat and other supplied heat that can be utilized. The capability of the atria to utilize heat from lighting and fans is calculated on the basis of measured operating times and outputs.

In addition, a calculation is made of how the heated atrium affects the total transmission losses from the building. It is assumed that the reduced transmission losses are proportional to the difference in insulation standard between walls facing the courtyard and exterior walls and to the difference in temperature outdoors and inside the courtyard.

Yet another question that has been studied is how the utilized energy in the atria could have been utilized without any atrium. This is a decisive factor in estimating the function of the atria from the standpoint of energy technology. Heat transmitted via the hollow core floor slabs is measured as airborne heat and reported as both a monthly and an annual sum.

Evaluation

The evaluation is based on data from measurements made from 1985 until 1988. In the building there are approximately 200 permanently installed measurement gauges of different types. The measurement values were stored via a computerized measurement system in the form of hourly values.

During the introductory period until the turn of 1986/1987 the offices were not fully staffed. During this period, moreover, operational disruptions have affected the facility. For this reason measuring results January 1987 and forwards are deemed to be most representative of the system.

To assure the quality of data extensive checks of gauges and measuring values have been carried out.

In the planning of the installation, a consistent objective has been for individual gauges and calculations of energies to be comparable against a reference. This can be done, for instance, by locating two gauges side by side or by measuring energy balances across a component in the system, for instance energy to and from a heat pump or a heat exchanger.

Equipment and data map

All the temperature gauges used in the Stockholm project are required to have an inaccuracy lower than ± 0.06 K. The total inaccuracy is nevertheless primarily dependent on how the gauge is placed at the point of measurement.

For measurement of electrical energy, use is made of class 2 gauges, which have a marked inaccuracy lower than ± 2%. Current transformers to electricity gauges are assumed to have a maximum error of less than ± 0.2%. The total error is therefore less than ± 3%. The electricity gauge emits one pulse per unit of energy registered by the measurement computer.

Liquid-borne energy is measured by one flow meter and two temperature meters in each energy section. The flow is measured analogously with the electrical energies by registration of pulses corresponding to a certain swept volume. For liquid-borne energy in normal operating conditions, the inaccuracy is expected to be less than ± 5%, including errors from gauges.

Air flows are registered by means of differential pressure measurement in the air ducts.

Owing to uncertainty as to how large a part of the office air to the atrium is returned to the offices, tracer gas measurement was performed in April, 1988. The result from this tracer gas measurement indicates how large a proportion of the air flow through the atrium consists of return air on the one hand, and of mixed outdoor air and exhaust air from the residential apartments on the other hand.

For airborne energy, the inaccuracy is normally calculated to be less than ± 10%. This applies when allowance has been made for sources of error from flow measurement, temperature measurement, calculation of thermal capacity and density. The relatively high inaccuracy is due to the fact that the requisite straight stretches before and after the measurement section have not always been available.

The inaccuracy of the measurement station has not deviated by more than ± 1% during the measurement period.

Checking of gauges is normally performed in three stages: prior to installation, in conjunction with commissioning of the facility and, in some cases, after removal.

The availability of measuring data has been very high. The longest period, roughly 6 days, during which measurement values were not obtained occurred during the autumn of 1987. Apart from this, only individual hourly values are lacking on a few occasions. When adding the hourly values together into, for instance, monthly sums, all missing values were replaced by the mean value of existing hourly values for the month concerned.

Findings

With regard to the anticipated function of the combined glazed atria as a cooler and solar collector, it was found that these effects were influenced by the atrium being heated more than calculated. The unanticipated increments consist mainly of heat from the substation, atrium lighting and heat from fanwork. All in all, the extra increments have been estimated at approx. 120 MWh, roughly 60 per cent of the total amount of heat supplied to the atrium. The values apply to the heating season October 1986 - May 1987.

The measured atrium temperatures were appreciably higher than those originally calculated. The calculated mean temperature for the heating system, based on the climatic conditions prevailing in 1971, was approx. +11 °C. The measured mean temperature during the corresponding period of 1987 was slightly more than +16 °C.

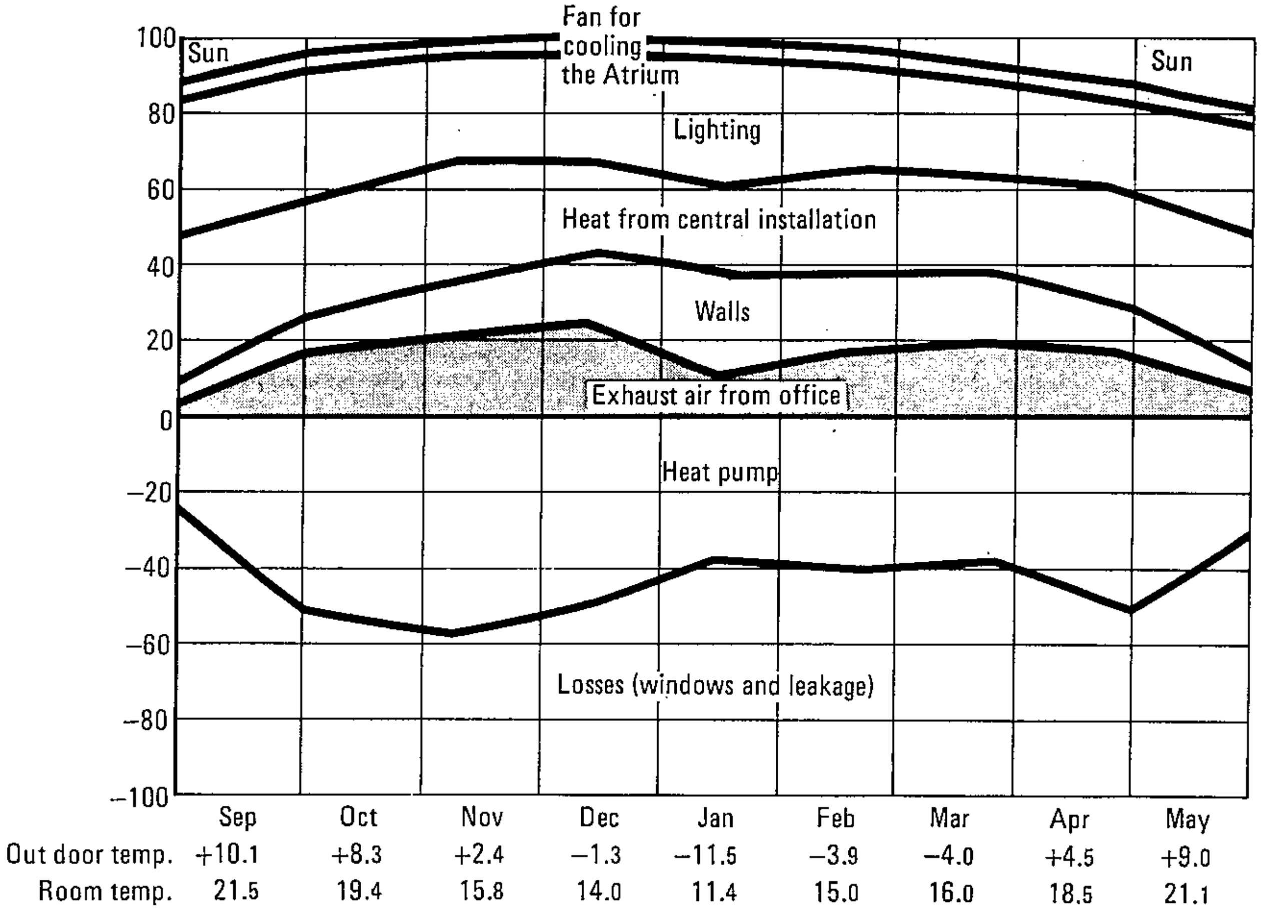


Fig.3 Percentage energy balance and temperature conditions in the atrium and outdoors, based on measurement results from 1987 (monthly values).

In summing up, it may be said that the total contribution of the experimental measures that has been achieved with the aid of the hollow-core floor slabs, the glazed atria, and lower transmission losses, amounts to between 80 and 90 MWh per year. This is to be compared with advanced calculations and the original hypothesis, according to which this contribution would amount to some 175 MWh.

The experimental measures afford a total contribution of around 12 kWh/m^2, year, equivalent to some 10 per cent of the purchased electrical energy during 1987. The total contribution from the heat pump in the form of recovery from exhaust air including atrium air has been measured at approx. 40 kWh/m^2, year, equivalent to roughly 30 per cent of the purchased energy.

The air tightness of the building envelope has been tested in one apartment. On measuring at negative pressure and with a pressure difference of 50 Pa, the air change rate was 0.90 per hour. With "support pressure" in adjacent apartments, the air change rate was 0.79 per hour.

In the tracer gas measurement in the combined atria, a known amount of tracer gas was supplied to the office air which, in its turn, was supplied to the atria. At the same time, the concentration of tracer gas was measured in the flow from the atria to the offices. The measurement was performed under stable conditions for about 4 hours. The measurements show that the proportion of returned office air from the atria amounts to approx. 75-80 per cent. The remaining 20-25 per cent thus consist of outdoor and/or exhaust air from the residential apartments.

The total amount of energy purchased in 1987 for both the residential apartments and the offices is approx. 130 kWh/m^2 and year (see figure 4). 112 kWh/m^2 and year was supplied to the offices. Almost 50 per cent of the energy purchased for heating of the offices consists of electric radiators for cold- draught protection. The offices are equipped with mechanical supply and exhaust air ventilation, which means that a conciderable amount of electricity is needed to run the fans. The proportion of general lighting in the item "building services" is relatively low. Lighting for office activities as such is included in the item "office electricity".

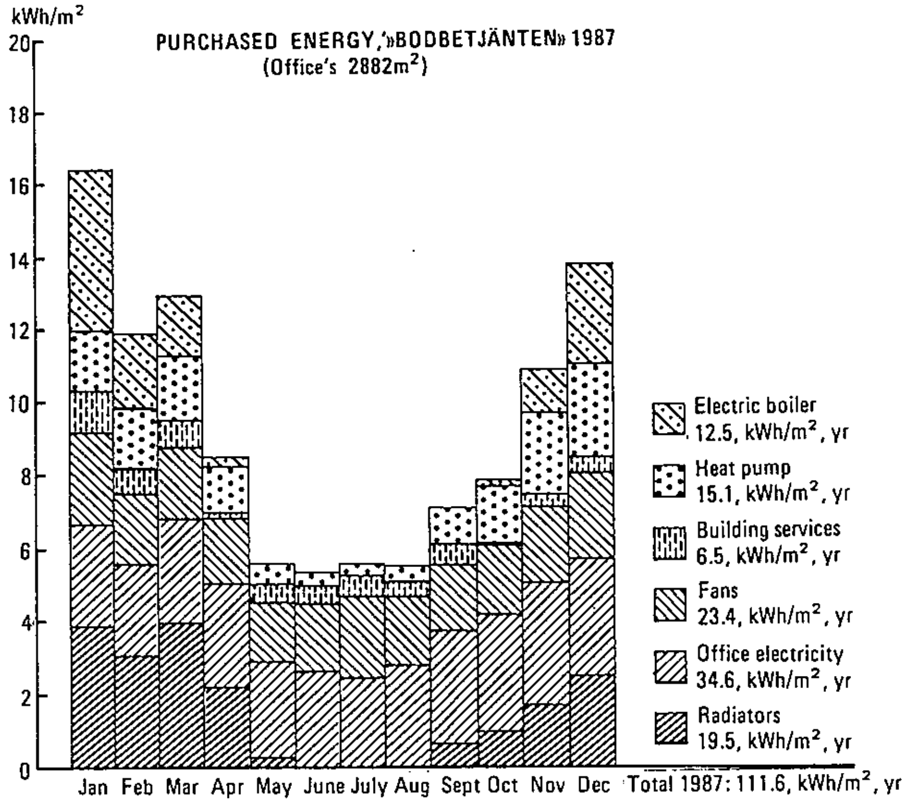


Fig.4 Purchased energy to the office part of "BODBETJÄNTEN" 1987

Office electricity, i.e. electricity for appliances and lighting in office premises, comprises the largest single energy item charged to the offices. The greater share of this energy benefits the offices in the form of heat during the heating period, but constitutes a cooling load during the summer. As evident from figure 4, a large part of the purchased energy for the building consists of electricity for the operation of fans. In the item "building services", pumps and lifts, among other things are included.

The total level of purchased energy is relatively low as compared to ordinary office buildings of the 1980s. The main reason for this is the contribution from the heat pump to heat production.

Part of the explanation of the low energy use for the offices is that they are only occupied during daytime hours and that both installations and the control system are capable of adapting energy and air supply efficiently to match the need. Moreover, the location of the offices and utilization of night-time cooling means that high energy consumption for cooling requirements is avoided.

The low energy consumption is also attributable to the fact that the offices are ventilated with a large proportion of return air via the atrium during the heating season. Some 80 per cent of the total air change rate of about 2.5 changes per hour during office hours consists of return air. When viewed in the light of a climatic hygiene perspective, this state of affairs is obviously open to question.

4 SIMULATIONS

Input assumptions

The calculations embrace the heating season with climate data for Stockholm, 1971.

The energy is reported monthly. In the project, only intermediate storeys have been processed with the calculation program BRIS. Heat losses through roofs and basements have been added afterwards.

Calculation results

The total amount of purchased energy is calculated at 81 kWh/m2 and year. The energy from the electric boiler is divided into about 45 per cent for heating of the residential apartments and about 55 per cent domestic hot water. Leakage losses plus transmission is below that of the majority of comparable buildings, thanks to the buffer effect of the atria.

The total monthly energy balance is evident from Figure 5. The heat pump covers some 60 per cent of the heating requirement during the heating season.

The importance of supplying exhaust air to the atria from the offices during December-January is clearly evident from Figure 2, showing the calculated energy balance for the atria. During the other months of the year the solar increments are of increasing importance for the heat balance. Energy to the heat pump accounts for some 60 per cent of the energy balance of the atria, even during the coldest months.

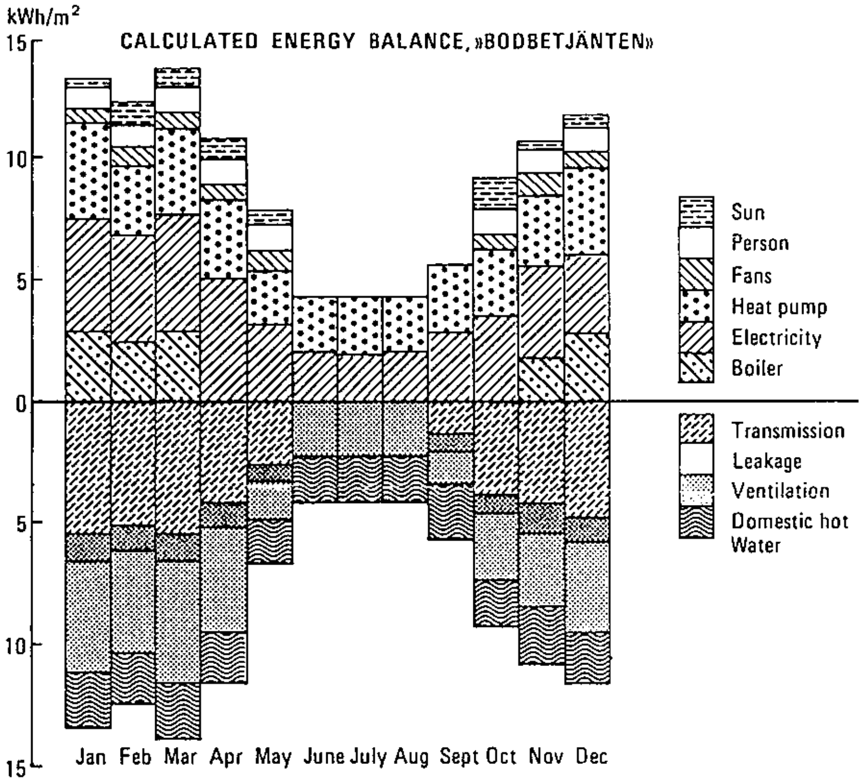


Fig.5 Total energy balance as simulated, monthly, Bodbetjänten.

5 CONCLUSIONS

The location of the offices, north of the residential apartments and with windows facing largely north, has significantly reduced the cooling requirement. The effect is difficult to quantify, but in view of the low measured cooling effect during the summer months the northern situation is of great importance.

Lowering of the temperature at nights, together with the technique of supplying the supply air via hollow-core floor slabs means that some cooling effect is also retained during day-time.

This has led to the share of surplus heat in the offices being lower than anticipated.

When surplus heat has been available, the possibilities of transmission via the hollow-core floor slabs has been limited by an unexpectedly high temperature level in the residential apartments, with a mean value of approx. 22-23 °C, and small and only temporary differences in temperature between the offices and the dwellings.

Although the atria are not heated solely with free or recovered energy, the availability of a heated courtyard during the winter is probably of value in itself. It is nevertheless important to emphasize that a large part of the heat supply, some 50 per cent, equivalent to about 15 kWh/m^2(atria) and year, actually consists of purchased energy. This is primarily due to the following factors:

- the atria has such limited light inlets that this must be compensated for with conventional lighting and plant illumination even during daylight hours. This supplies a good 40 MWh during the year - some 25 per cent of the total heating of the atria.
- fan electricity is appreciable and accounts for some 20 per cent of the supplied energy to the atrium.
- supplied heat to the atria from the offices during normal operating conditions must be replaced to the offices.
- the raised temperature in the atria, as compared to the simulations, reduces their capability of utilizing "solar and surplus heat" and increases the transmission losses from the atria.

TWO STUDIES OF WASA CITY

Gavle, 60°N, Sweden

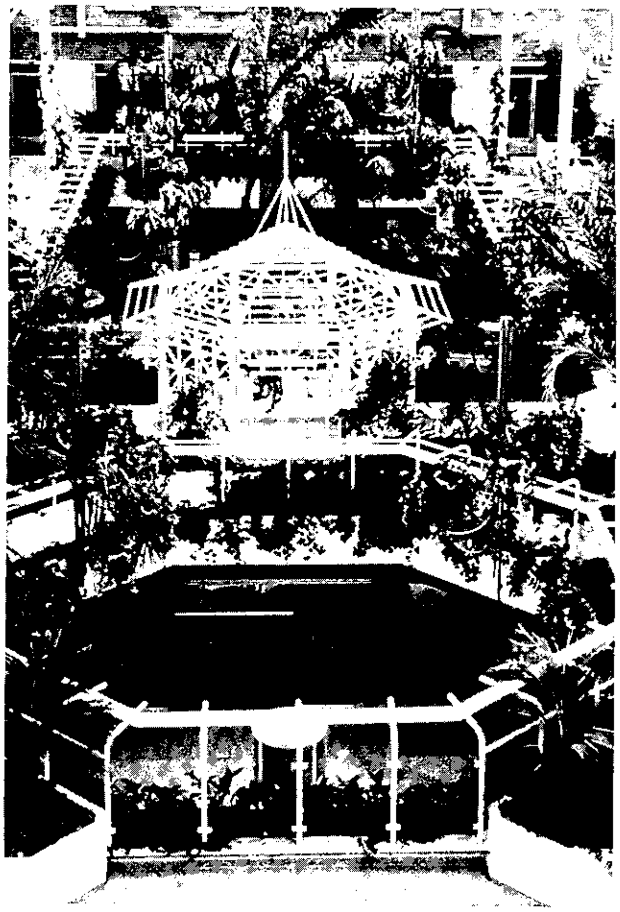
The Energy Balance of a Glassroof — Mauritz Glaumann
Living in a Glass House — Ulla Westerberg

Introduction

In our latitudes weather and seasonal changes govern social life; during a large part of the year we live indoors. Today a growing number of atriums are being built as an energy saving way of creating big, weather protected social spaces. The atrium in Wasa City is examined from two different angles - as a social space and in terms of energy.

The first study deals with the problem of examining the heat flow through the glazing. Even sophisticated models for energy balance mostly treat the environmentally dependant radiation and wind conditions very briefly. Our aim is to show the influence of local climate on the heat balance of a glass roof by means of measurements.

The second study deals with the special environmental qualities of the atrium - neither indoors nor outdoors - and its consequences for the physical and social climate. Based on the experience of the tenants, we wanted to find out how it affects residential space.



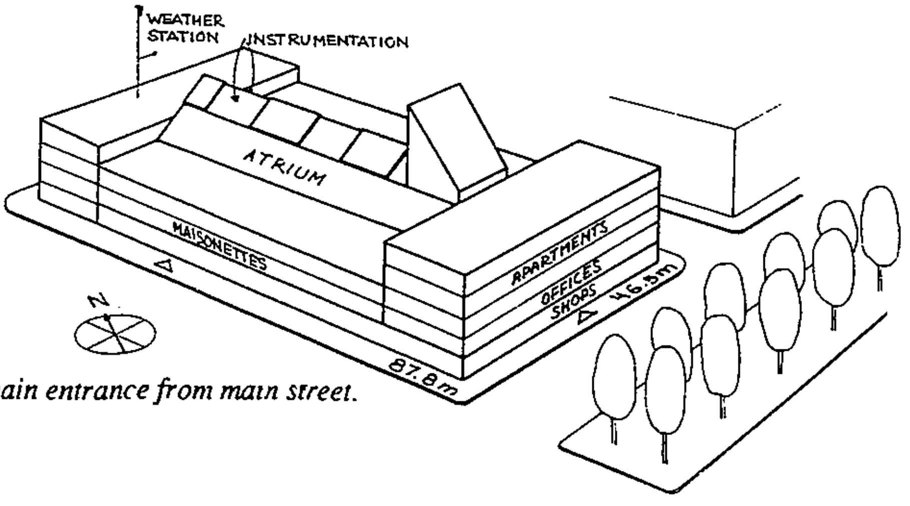
Building description

Wasa City was built in 1965. It was rebuilt in 1987, and the open rectangular courtyard in the middle was glazed-over in order to obtain an attractive inside-square on the ground level and a winter garden above for the upper floors. The building and maintenance costs were to be payed by the commercial activities, not by the residents.

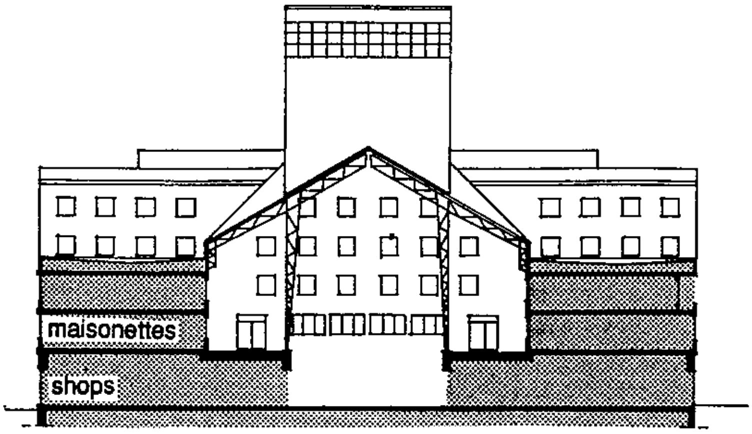
Wasa City is located in the very centre of Gävle, a medium-size Swedish city on the baltic coast 200 km north of Stockholm. The quarter is surrounded by streets with heavy traffic. The nearest park bench can be found in the city square which is on the other side of a major thoroughfare. The entire ground floor of Wasa City is occupied by commercial enterprises which to an extent spill over into the atrium: a big book store, a florist, a ladies' wear and some other small shops and a restaurant. The atrium gives quite an exclusive impression. It is light, spacious and green. The commercial ground floor has benches and decorative water works and opens up to the residential wintergarden on the second floor with a great many plants.

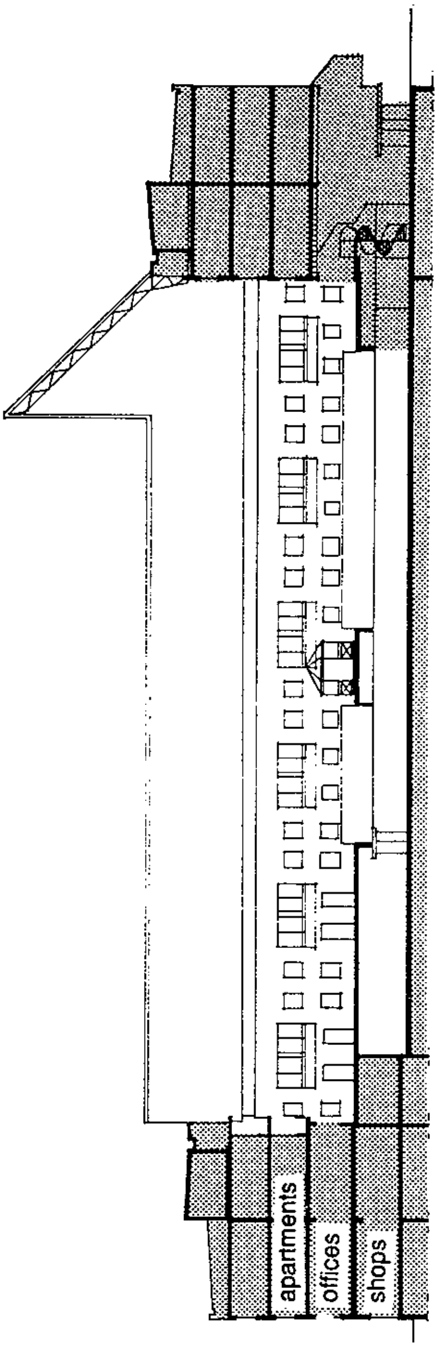
On the second floor, above the shops, there is a wide deck with maisonettes with private patios along the long sides of the atrium. Apartments are situated in the upper levels of the short sides of the atrium around a central stairway, which is also used by maisonette tenants. In the two higher buildings on each short side of the courtyard there are offices and ordinary apartments with access from stair-cases, which are also used by the tenants in the maisonettes. Altogether there are some 50 dwellings with 1 to 5 rooms and a kitchen. The design of the them was neither initially planned nor altered during re-building to take consideration of the atrium. Kitchens, bedrooms, livingrooms, patios, balconies may face the atrium.

The atrium maintains a year round temperature of between 16° and 25°C. However, when faults have occurred with the automatic roof shutters, the temperature has risen to over 30°C in the summer. The glazing in the courtyard, almost 1 800 m^2, is large in relation to the atrium volume, 160 000 m^3. The horizontal area is 1400 m^2. The space is mechanically ventilated with approximately 0.5 air changes per hour, and heat is recovered from the exhaust air. To keep the night minimum temperature at $16^{\circ}$and the day minimum at 18°C. There are 30 kW floor heating and 50 kW radiators at the eaves. In the ceiling there are 100 m^2 partly opaque shutters which are automatically opened for natural ventilation and in case of fire and overheating. Light curtains act as sun protection. They are governed by an internal daylight sensor. The main part of the glass roof is pitched facing northeast, 60°, and southwest, 240°.

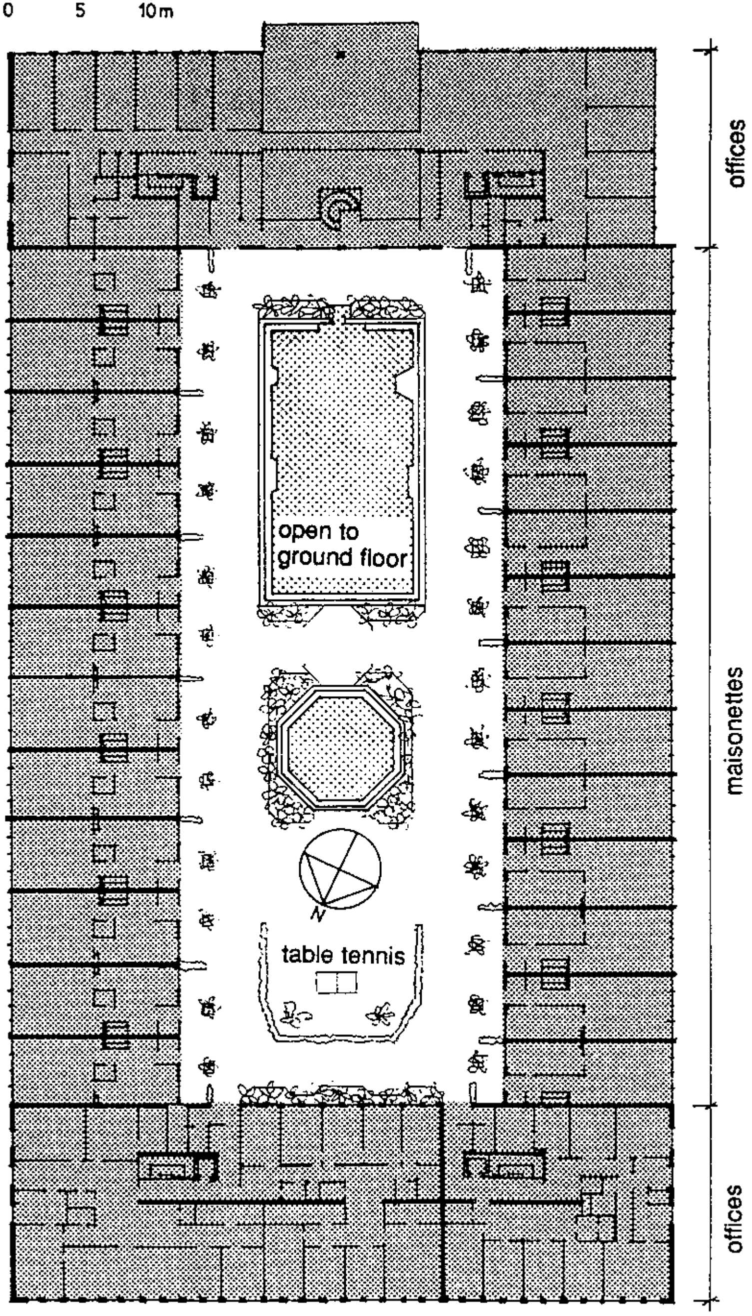


Wasa City, main entrance from main street.





WASA CITY



LAYOUT PLAN, WINTERGARDEN, 2ND FLOOR

Abstract

THE ENERGY BALANCE OF A GLASSROOF

The energy balance of a triple-pane glass roof has been measured over one winter, one spring and one summer period. The results have been analysed as regard radiation balance, convective heat flow and U-values. The terms of balance were later stepwise correlated to the external climate variables - solar radiation, long-wave counterradiation, ambient temperatures and humidity.

The 30° tilted glassroof had an average U-value during the period of loss that was 5-6% greater than for the corresponding vertical glazing, mainly because of greater nocturnal radiation losses to the sky. About 40% of the incident solar radiation on the glassroof heated the atrium in Wasa city. Wind had only a slight effect on the heat loss through the glazing. But it counteracted increased heat losses during clear nights through tranfering heat from the air towards the emitting glass surface. Simulations show that the heat losses in heated atriums increase heavily the further north they are situated. The vertical glazing has a more favourable energy balance than the tilted glassroof on high latitudes.

Regression gave the following simple equation for our triple-pane construction:

$$Q = -37.1 + 0.44K + 0.09L - 1.2(t_i - t_o)$$

where Q is the energy flow, K, the perpendicular solar radiation, L, the long-wave counter-radiation and t, the air temperature inside and outside.

LIVING IN A GLASS HOUSE - Residents' Views - Design Recommendations

Using the residents' experiences as our point of departure, we wanted to investigate how the atrium is used and experienced and compare our results with other studies of atriums. Can the weather-protected atrium compensate lacks in the outdoor environment and a cold outdoor climate? What are the effects of the atrium on interior living space? Does the commonly-shared atrium influence contacts between tenants? With these questions in mind, we sent a questionnaire to all the tenants in 1989.

Responses to the environment in the atrium were positive, but responses to the climate inside the atrium were largely negative. The majority of tenants had a positive opinion of the atrium in general. Those who had moved in after the retrofit and those having their own patio in the atrium were throughout more positive. Spontaneous comments and answers to specific questions were most often negative. What is satisfactory has been more difficult to discover and formulate.

From the results of our study we have drawn the following conclusions: Even in residential blocks, the atrium should provide a winter garden; it is then a good alternative in a heavily trafficked, congested city environment, possibly also with commercial activities that can help with costs for heating. In balcony-access blocks, maisonette apartments provide better sun- and daylighting and more privacy/better protection from outside view than ordinary single-level apartments. Private external spaces (patios) in the atrium should be given priority - afterwards common external space may be considered.

THE ENERGY BALANCE OF A GLASS ROOF,

EVALUATION LEVEL

Objective

Our aim is to show and discuss the energy balance of glazing, guided by better information on wind and radiation conditions than is normally available. Our hypothesis is that heat losses per m^2 from a glass roof of a certain construction are higher than from a window with a corresponding construction, i.e. the U-values for windows cannot simply be applied to a glass roof. Losses through radiation are larger because the roof "sees" a larger part of the sky than does a window. In addition, roof surfaces and corners are often exposed to greater wind velocities than facade windows.

Since the regressions made are based on real indoor temperatures, the energy calculations apply to the real gains/losses with the natural swings of indoor temperatures with solar radiation and with heating up to 16°C at night and 18°C during the day. Derived relations thus include the heat storage in the atrium.

The energy balance

Through the glass roof heat, Q, is conducted to and away by means of:

1. Long-wave heat radiation, L, and short-wave solar radiation, K. The sum is denoted as N.
2. Convection, i.e. heat exchange via the air near the surface, Q_H.
3. Water and vapor transfer, i.e. heat exchange via the latent heat of fusion or the latent heat of vaporization, Q_E (condensation, evaporation, frost and sublimation).

The amount of heat that passes through the exterior surface must be equal to that passing the inside, i.e. $Q_o = Q_i$. During dry weather $Q_E = 0$. Inside, no latent heat transfer occurs via moist. At night there is no short-wave radiation and consequently no direct radiation transmission. If the heat which is conducted through the glazing is called Q_C and * denotes the net sum, we have the following during the night:

$$Q_C = N_o^* + Q_{Ho} = N_i^* + Q_{Hi} \qquad (1)$$

The convective heat flow inside and outside can thus be determined for nights from the measurements of heat flow, Q_C, and net radiation, N^*. However, during the day solar radiation is absorbed by the glazing and we do not know how this heat is distributed in radiation and convection inside and outside. Consequently, we wish to obtain a relation between the convective losses during the night and the temperature gradients and air velocities which we have measured next to the glass surfaces. We should be able to apply such a relation also during the day.

The energy balance of the glass roof which we are seeking can thus be determined either internally or externally. However, it was difficult to obtain from the measurements a general relation for convection externally, so we have primarily tried to determine energy flow on the inside, where convection varies significantly less.

Our ambition has been to measure the components of the energy flow at the inside and outside of the glazing and at the same time, measure the climate variables which are standardly observed. In particular for these measurements has been that we have used net radiation meters, which on the inside, directly give the contribution of radiation to the heating or cooling of the atrium.

The energy flow, including latent heat transfer, i.e. $Q_E \neq 0$ will not be dealt with here.

Monitoring Periods

Measurements were carried out during three periods during the beginning of 1989: 11/1-3/2; 17/3-20/4; and 9/6-7/7. We shall primarily discuss the heat balance of the glazing during the heating season. The results reported are based on winter and spring measurements.

As regards the analyses below we have excluded times when precipitation has been registered at the meteorological station at Utvalnäs, 12 km outside of Gävle. Likewise, we have excluded those hours when the dew point was near the glazing's external temperature according to our measurements. In correlations with meteorological observations we have only been able to use those occasions when simultaneous observations were being made at Utvalnäs, i.e. every three hours.

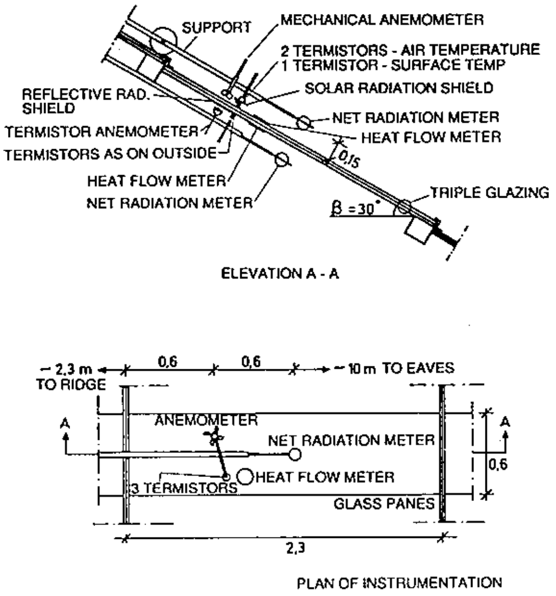
The winter period was remarkably warm, with little precipitation and fairly windy. Air temperatures averaged 3.4°C (max. 8.7, min.-1.9); wind velocity at the glazing was 2.5 m/s; solar radiation during the day, 68 W/m^2 and counter-radiation, 270 W/m^2. The wind was basically SW-W.

During March it was also relatively windy and mild with temperatures above zero. The beginning of April was colder. Thus the lowest outdoor temperatures were measured during spring, not during winter. In mid-April there were summer temperatures for a few days. Large amounts of precipitation have meant that fairly many hours had to be excluded. Air temperatures averaged 5.6°C (max. 22.0, min.-2.8), wind velocity at the glazing, 2.0 m/s, solar radiation during the day was 321 W/m^2 and counter-radiation, 263 W/m^2.

Our samples were taken every other second for wind sensors and every minute for other sensors. All analyses were made with mean values per hour.

Measuring equipment

All measurements taken from the glazing were made on the inside and outside within ca 1m² on both the northeast(60°) and southwest(240°) facing sections of the roof. Figure 1 shows the arrangement of the instriments.



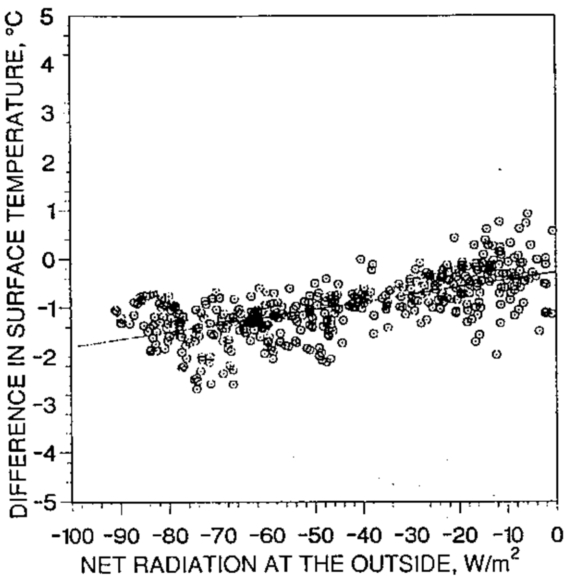


Figure 1.
Instrumentation at the glass roof.

Figure 2:
Measured difference in surface temperature between sheltered and unsheltered sensor during nights.

To determine net radiation we have used a net radiation meter (Siemen Ersking). Convection could not be measured directly; we measured the temperature gradient (thermocouples) from the surface and ca one centimeter away as well as wind velocity immediately next to the glass surface.

Surface temperatures were measured with a thermocouple soldered to a small copper disc painted white and fastened to the glass with silicon. These and two air temperatures, also measured with thermocouples, were shielded from solar radiation by white-painted circular discs.

Parallel control measurements beside each other, one with a shade disc, the other without, showed that the surface temperature under the disc became higher than that next to it under a clear night sky, fig. 2. Increased wind velocity diminished this difference. We found that the following correction of the surface temperatures on the outside gave the best correlation with the heat flow:

$$t_s(\text{corr}) = t_s + 0{,}025\, N^*/v^{1/2} \qquad \text{night}$$

$$t_s(\text{corr}) = t_s + 0{,}004\, N^*/v^{1/2} \qquad \text{day}$$

v = wind speed at the exterior glass surface

Net radiation comprises an essentially minor part of the daytime correction since it mostly consists of solar radiation of which only about 20% is absorbed by the glazing. The maximum correction at night was -1.5°C and during the day, +2.3°C.

Heat flow sensors (TNO WS 31S) were sprayed white and attached by spring tension onto the glass with vaseline in between. It was apparent that they were unusable during the day as they were heated more by solar radiation than by the glass. A thorough calibration with the exact same glazing and positioning of sensors was made in a "hotbox". The heat flow sensors showed themselves to be sensitive to wind.

In order to also obtain information on the heat flow during the daytime a correlation was made between the heat flow measured on the inside of the glazing and surface temperature differences, fig. 3. The correlation seemed to be good and the heat flow was later calculated according to this regression line.

Solar radiation against the glass on the south side was measured with a photorotaic pyranometer sensor, LI.200S. Wind velocity above the glass was measured with a cupanemometer calibrated in our wind tunnel. Its starting threshold is fairly high, 0.5m/s. We assume that velocity values under 1 m/s are not totally reliable.

Air movements immediately inside the glass were measured with thermistoranemometers, made by our laboratory for studies of weak air movements indoors. They are sensitive to temperature gradients over the sensor. We protected the sensor from radiation from the cold/warm glass during the night/day with aluminium foil glued to the glass.

As a weather station we have used a 3-component wind sensor (propeller Gill), a fan-ventilated temperature sensor, 2 m and 10 m, an electric humidity meter (Rotronic MP-100) plus two thermohygrographers as controls. Cloudiness was observed on site at 7 o'clock, 13.00 and 19.00 and every three hours at the meterological station at Uvalnäs, 12 km northeast of the Wasa building.

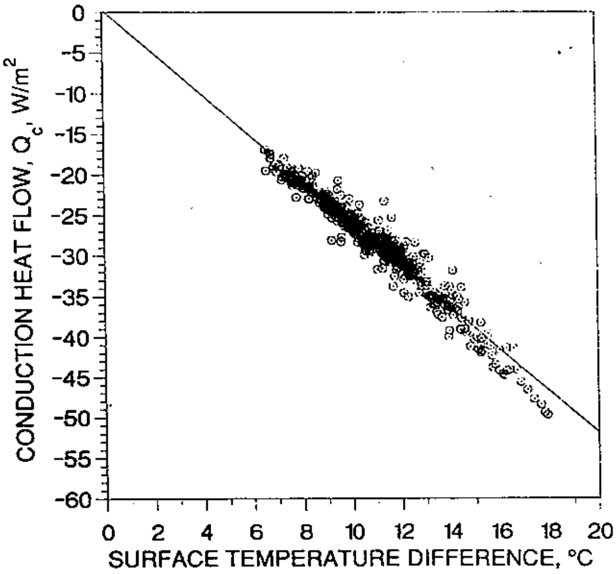


Figure 3.
Measured heat conduction through the glass roof versus difference in surface temperature during nights.

MEASUREMENTS

Radiation balance

Figure 4 shows an example of radiation balance on the outside of the glass during a clear and a cloudy day in April. 150-300 W/m² of the incoming solar radiation was reflected and absorbed-emitted back to the sky. The glass absorbed up to almost 200 W/m² of the incoming radiation. At most 150 W/m² was convected away mostly from the outside surface. Some 40% of the solar radiation actually heated the atrium. During the clear part of the night 60 W/m² at most was lost to the clear night sky. The long-wave radiation losses from the atrium to the glass roof were 20 W/m² during the night. During the totally overcast second day, radiation on the glass roof was at most 100 W/m², but only some 20% contributed to the atrium heating.

Convective heat flow

The convective heat flow between surface and air is usually described through the expression:

$$Q_H = h_c(t_s - t_a) \quad W/m^2 \qquad (2)$$

t = temperatures on the surface and air respectively
h_c = convective transfer coefficient

The convective heat transfer coefficient, h_c is dependent upon the geometry and surroundings of the surface and of the temperature, direction and velocity of the air. Particularly decisive is whether the flow is laminar or turbulent.

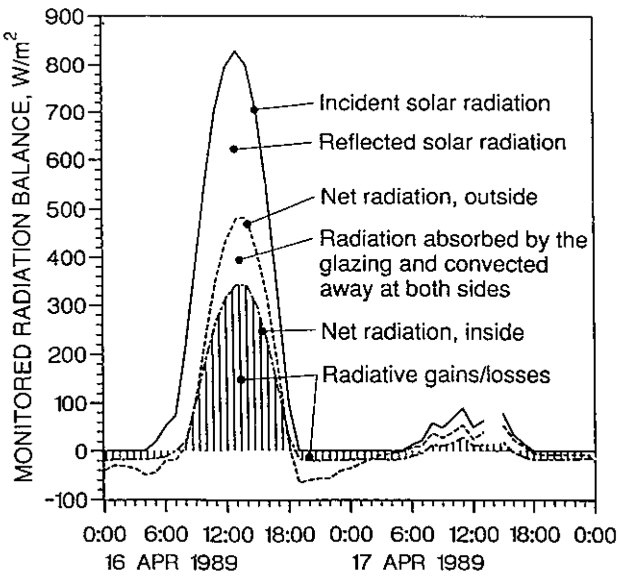


Figure 4.
Monitored radiation balance at southwest-facing glass roof in April.

Analysis of the forces involved and the characteristics of the air indicate that h_c should be an expression of the form:

$h_c = c_1 v^{c_2}$ for forced convection
$h_c = c_3 (t_s - t_a)^{c_4}$ for natural convection

c_n = constants depending on geometry and wind direction

c_1 is given as ca 2-7, c_2 as 0.5-0.8; c_3 as ca 1.6 and c_4 as 0.25-0.35 (Furler et al. 1988).

At the same time there are a number of empirical expressions for h_c applied to buildings which take the form:

$$h_c = c_5 + c_6 v^{c_7} \qquad (3)$$

c_7 as a rule is equal to 1.0, c_6 varies between ca 0.5-6 and c_5, between 1-11.

The very large spread of results from various authors shows that the prerequisites and measuring methods in most cases have been very different. For use in a certain instance where wind velocity and temperature differences are measured at certain points, previous experiences provide little guidance.

One difficulty with determining the interior heat transfer coefficient h_c has been that the air velocities were so low during the night. Thus we began with correlating Q_{Hi} for nights with only temperature gradients next to the glass. The correlation coefficients varied between R=0.85 to R=0.91 for the different sides and periods. The slope of the regression line was 5.4-5.8 for the north side and 5.3-5.7 for the south side. Air velocity averaged at 7 cm/s just inside the glass. We consequently know that $h_c \sim 5.5$ at that velocity.

Then we tried different expressions of the types mentioned above and obtained the best correlations with the following relation:

$$Q_{Hi} = (c_1 + c_2 v)(t_s - t_a) \quad \mathrm{W/m^2} \qquad (4)$$

$5.0 < c_1 < 5.5$ and $c_2 \sim 4$ for different sides and periods.

This resembles empirical expressions for forced convection but also agrees in size with other equations for natural convection. This has allowed us to use it also for daytime when convection is governed by rising air around the atrium's heated floor and walls. Even if the expression would correspond rather badly under strong insolation, this is of relatively minor significance since the convection on the inside is then a small part of the total energy flow.

During the night and on cloudy days the inside convective losses were steadily about 15 W/m^2, fig 5. But with strong insolation the inner glass was heated so much that its temperature rose faster than the inside air temperature, and the inside convective heat flow turned towards the atrium. However, after a few hours the rising air again became warmer than the surface. During clear nights the exterior convective flow turns towards the glass and partly compensate for the radiative losses. On the clear day the convective losses grow considerably when the glass is solar heated and the air layer above becomes unstabilized.

Energy Balance

The course of the energy flow that was seen at the inner surface is illustrated in fig. 6. On a clear day the radiation totally dominated the energy flow, while during cloudy days and nights convective losses within the atrium were responsible for about half of the energy losses. The radiative gain during cloudy days was further reduced by convective losses.

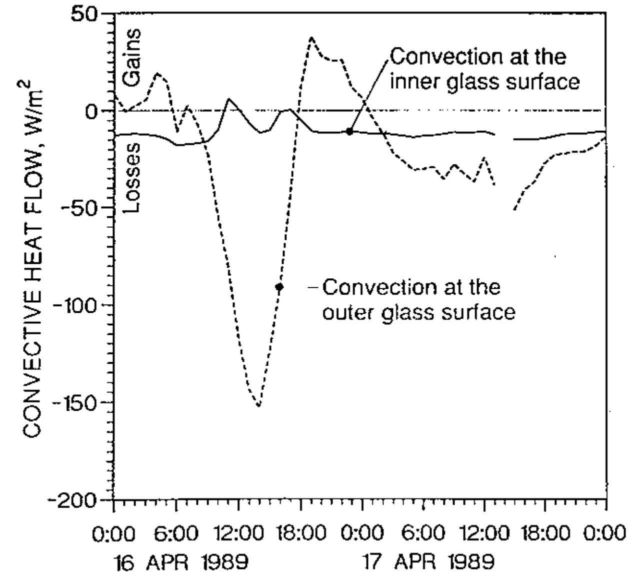


Figure 5.
Monitored and calculated convective heat flow in April.

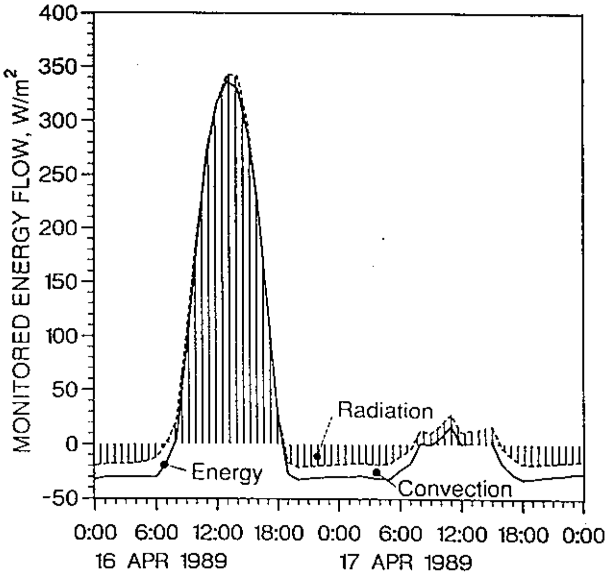


Figure 6.
Total energy/gains losses monitored at the inner glass in April.

Atrium temperatures

Heating of the atrium kept the temperature at floor level above ca 15°C. The large size of the glass roof in relation to atrium volume, however, entails that the temperature swung considerably with radiation conditions. The difference in temperature between floor and roof in the atrium was well correlated with the mean value of net radiation at both ceiling surfaces with a half hour time lag, fig. 7. If one knows the net radiation inside (later it will be shown how this can be calculated), one can tell what temperature stratification exists in the atrium.

During the spring days when measurements were taken it became at most 8.2°C warmer near the roof than at the floor level, and during the night, a maximum of 1.7°C colder at the roof than on the floor.

Heat transmission - U-values

Using U-values in calculations means assuming constant heat transfer coefficients at surfaces. However, to be equivalent to real heat flow, U-values should vary significantly with wind and cloudiness. The net radiation determined by cloudiness seems to be more important for the losses than the wind speed. The distribution of U-values during 534 winter and spring night hours is shown in fig. 8. The total variation was slightly above ±10%. Although great variance, the tendency is very clear that increased radiation losses increase the U-value. Increasing winds seem to slightly increase the U-value at cloudy conditions but rather decrease it or have no effect during clear conditions. Some of the variance may by explained by small differences in the position of the thermocouples at the different surfaces and during different seasons.

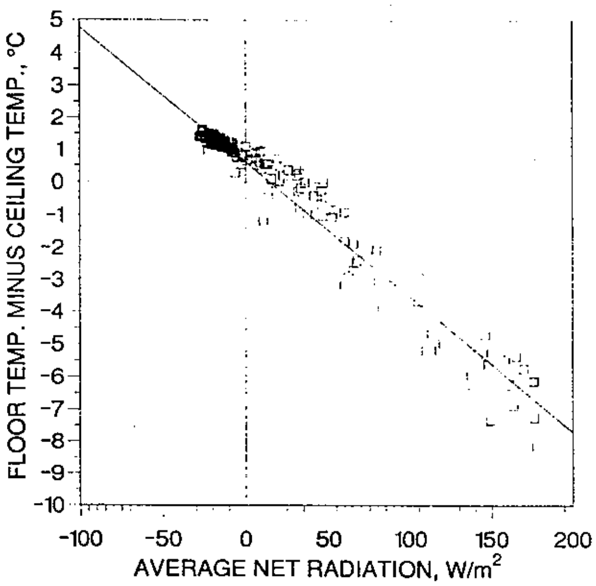


Figure 7.
Measured difference in air temperature at floor and ceiling level versus mean of inside net radiation for the two roof surfaces.

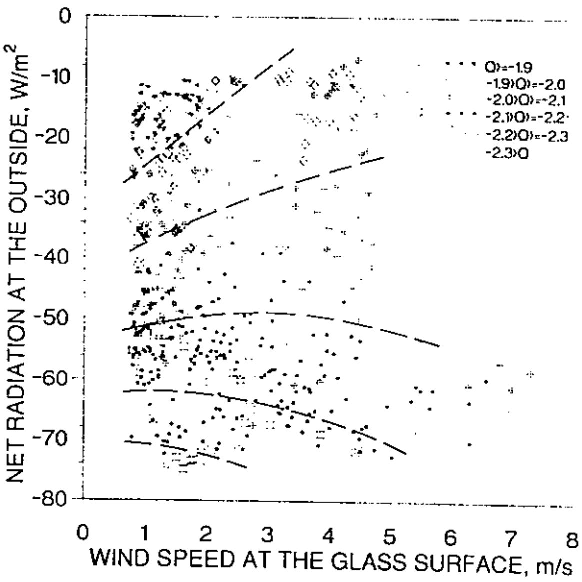


Figure 8.
U-values during 534 night hours in winter and spring as a function of wind speed and net radiation above the glass.

Winds at glazing

In order to be able to simulate convective heat flows later we had to know how much wind blew against the glass, with different speeds and directions. Measurement results are given in fig. 9. The heavy line denotes an average value which we have drawn by hand and then applied to the simulation of wind velocities on the roof.

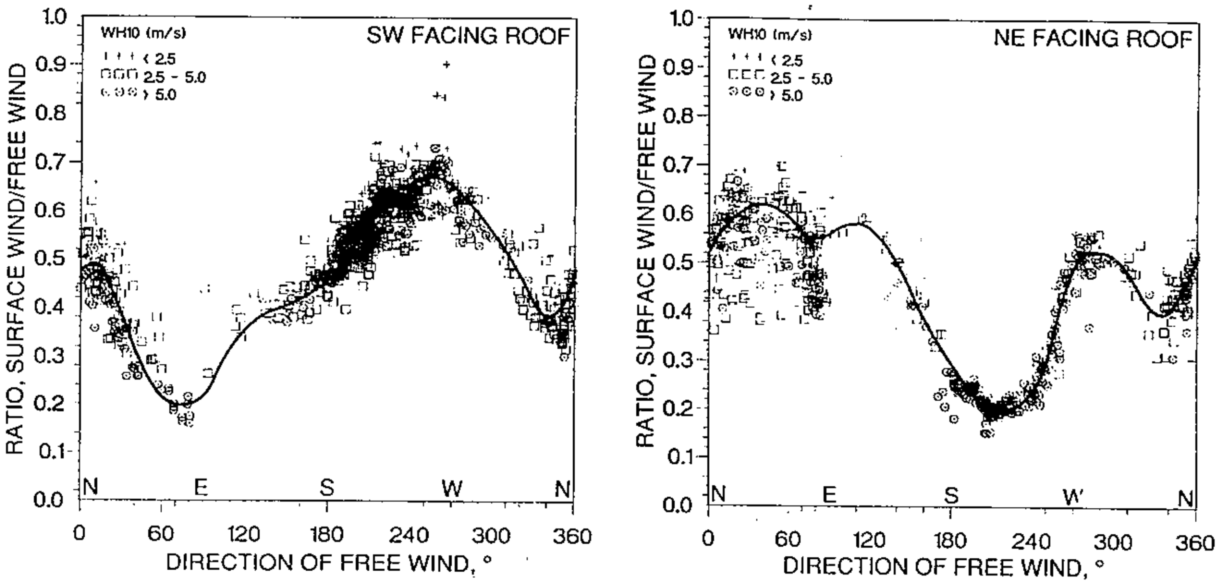


Figure 9. Hourly ratio between wind speed next to the outer glass surface and the free wind measured 10m above the roof. Only hours with surface wind speeds above 1.0 m/s.

SIMULATIONS

We wanted both to show how the heat balance of the sloping glass roof in different places and to show how the glass roof worked in relation to a vertical window. To do this we needed expressions for radiation and convection as functions of statistical climate variables.

Solar radiation

The solar beam radiations is easily transferred to beam radiation on any surface after calculating the angle of incidence. Diffuse radiation on the sloping surfaces we have calculated with an anisotropic (stronger diffuse radiation from the area around the sun disc than from the horizon) method presented by Taesler/Andersson 1983 (originally Hay).

Counterradiation

The long-wave counterradiation was calculated by means of air temperature, humidity and cloudiness. There are a number of different methods to assess this (Kamada/Flocchini 1984). Most of the methods are empirical and have been developed ever since the beginning of this century. As a rule, when determined a fictive sky emissivity one can calculate the counterradiation via air temperature by using Stefan-Boltzman's law. We have used a relation for the clear sky emissivity by Berdahl/Fromberg (1982):

$$L_0 = \sigma T_a^4(0.741 + 0{,}0062\ t_p) \qquad (5)$$

t_p = dewpoint temperature, °C
T_a = air temperature, K
σ = Stefan-Boltzmans constant

The Wasa roof slopes 30° and consequently does not "see" the whole sky. The proportions of sky and ground that the sloping surface "sees" are:

$(1 + \cos\beta)/2$ sky portion (6)
$(1 - \cos\beta)/2$ ground portion
β = slope towards the horizontal plane

However, measurements have shown that losses to the zenith area are significantly larger than towards areas near the horizon. Lauscher has calculated net radiation for surfaces with different slopes in relation to the horizontal (Geiger 1971), fig. 10. According to this radiation losses from the Wasa roof towards a clear night sky are 2.3 times greater than from a vertical window.

Since both the surroundings and the glass have emissivity factors near 1.0 and similar surface temperatures, we assumed that the long-wave radiation exchange with the ground was nearly zero. A difference in surface temperature of 2°C between the glass and the ground only gave a few percent difference in radiation exchange.

Thus we approximated counterradiation from the clear sky on sloping glass surfaces as:

$$L_{0\beta} = \sigma T^4(\varepsilon c+(1-c)) \qquad (7)$$

c = reduction of net radiation according to fig. 10.

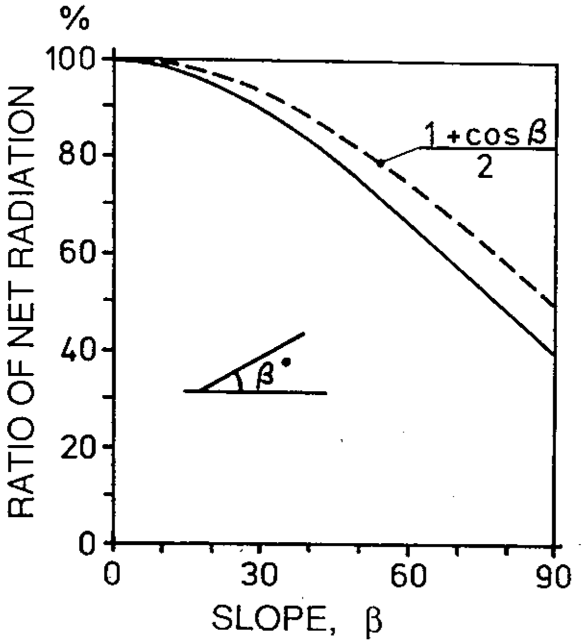


Figure 10.
Ratio of the net radiation from an inclined surfaces and that from an open horizontal surface (After Lauscher/Geiger).

To this was added the increase in counterradiation with increased cloudiness adopted from Oke, 1978 (originally Boltz 1948; see Geiger 1972):

$$L_n = L_0(1 + c_1 n^2) \qquad (8)$$

n = cloud cover in tenths

c_1 = constant between 0.04-0,25 depending on type of cloud.

Winds at glazing

For wind velocities at the glass surface we used the conversion figures for every 10° which are defined by the heavy line in fig 9.

Ambient temperature

The air movements and temperature gradients next to the glass determine the convective heat transfer. During a sunny day, it was up to ca 10°C warmer at the glass than at a 2 m level over the ground, while during a clear night it was seldom more than 2°C colder near the glass than at a 2m level. Hence we have mainly used the air temperature just above the glass in regression analyses. When we used official temperature data for simulations, we might get a slightly too high temperature during the night and a bit too low temperature during the day.

Stepwise regression

Stepwise regressions were carried out for measured data against the external climate variables. These were ambient temperature, dewpoint, solar radiation, counterradiation and wind velocity at the glass. The variables that contributed less than 0,1% to the correlation coefficient were excluded. In the following, the regression terms are ordered according to their significance.

For *net radiation* at night we obtained correlation coefficients between 0.90-0.94 and during the day, about 0.99. That the correlation was so high during the day is due to the net radiation being wholly dominated by solar radiation as an independent factor. For day and night together we got the following relation, fig. 11:

$$N_i^* = -27.94 + 0.43\,K + 0.072\,L - 0.56(t_i - t_o) \qquad (9)$$

n=178; R=0.99

The *convective heat losses* on the inside of the glass reached a maximum of ca 20W/m². During the day they were generally less than at night, and could even be turned into gains when the glazing is warmed up faster than indoor air. When calculating the convective heat loss according to equation (4) with c_1 = 5.2 and c_2 = 4.2 the relation became, fig 12:

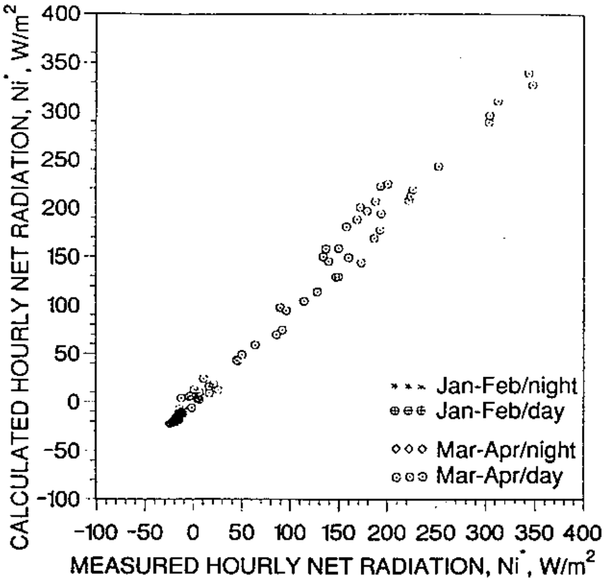


Figure 11.
Calculated net radiation versus monitored at the inside of the glass roof.

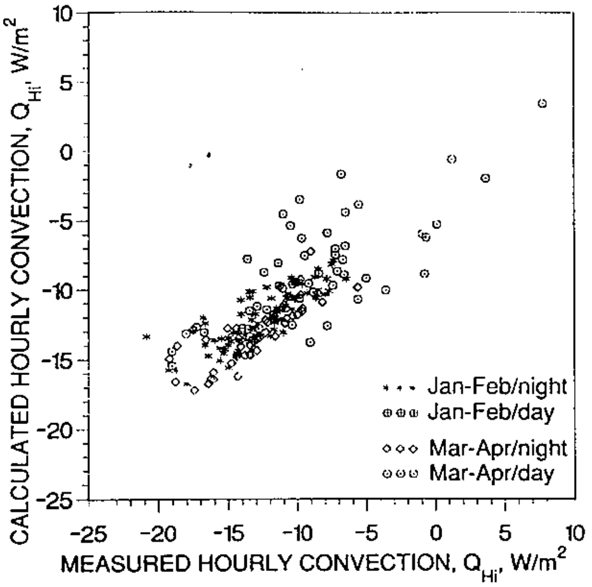


Figure 12.
Calculated convective heat flow at the inside of the glass roof versus monitored during nights and calculated during days.

$$Q_{Hi} = -10.67 - 0.61(t_i - t_o) + 0.0080\,K + 0.026L \qquad (10)$$
$$n=179;\ R=0.84$$

The regression equation for the *total energy flow* is more or less wholly in accord with the sum of the two foregoing expressions:

$$Q = -37.1 + 0.44\,K + 0.09\,L - 1{,}2(t_i - t_o) \qquad (11)$$
$$n=186;\ R=0.99$$

This shows that about 40% of the solar radiation contributes to the heating of the atrium.

In order to discuss U-values we must know the amount of heat that is conducted through the glazing. *Heat flow* as a function of the surface temperature difference according to fig. 3, appeared as the following, fig. 13:

$$Q_C = -\,10.62 - 1.87(t_i - t_o) - 0.013K + 0.034\,L - 0.046v_0 \qquad (12)$$
$$v_0 = \text{free wind speed, m/s} \qquad 202;\ R=0.95$$

The *indoor temperature* was needed to calculate all the flows. The lowest recorded indoor temperature was 15.7°C during nights and 16.4°C during winter days, and 16.7°C respectively 16.9°C during spring. No really satisfactory correlation can be expected for the indoor temperature partly because the atrium was heated to different levels during the day and at night. The automatic sun shading of course irregularly affected also the indoor temperature. We have made one regression in which we have forced the regression line through 14.0, fig 14:

$$t_i = 14.00 + 0.015\,L + 0.0077\,K - 0.20v_0 \qquad n = 162 \quad (13)$$

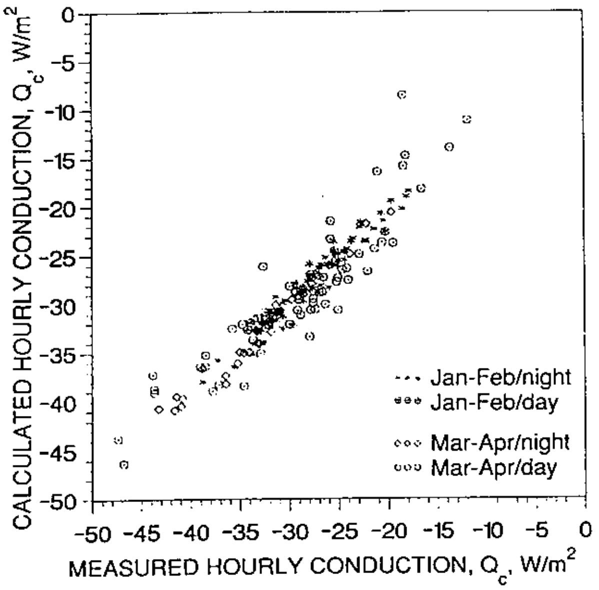


Figure 13.
Calculated heat conduction through the glass roof versus monitored.

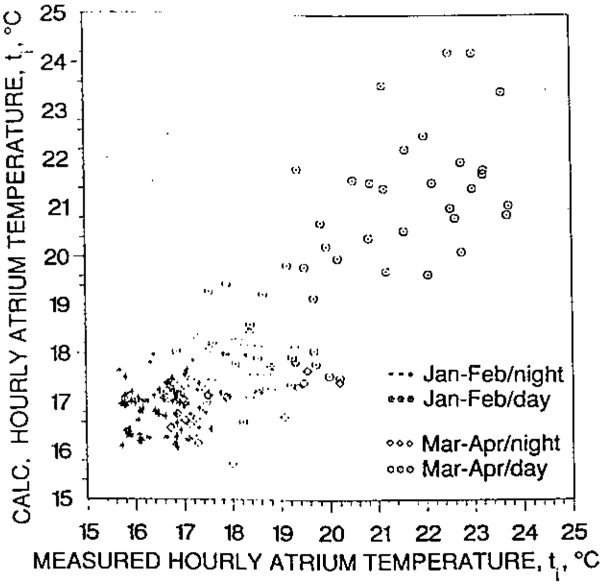


Figure 14.
Calculated atrium air temperature at floor level versus monitored.

Wind velocity here lowers the indoor temperature, which must be a consequence of air leakage in the construction (particularly the shutters) since we have seen that the wind plays a very minor role on the heat flow through the glass. The difference between recorded and calculated indoor temperatures were ca +-2°C. The significance of this is discussed later.

Results

The regression equations obtained were used to simulate hourly values for radiation, convection and U-values for Norrköping (ca 250 km south of Gävle) and Luleå (ca 550 km north of Gävle). The calculations were made for the actual year 1975 and not for any reference year. This means that the temperatures and solar radiation do not vary regularly over the year.

We were primarily interested in viewing the heat balance during the winter in order to assess what passive heating could be made use of in the atrium and what amounts of energy were required to compensate the heat losses through the roof when heating to the levels in question.

The total energy balance of the glass roof when located in Norrköping and in Luleå is shown in fig. 15. For the northeast-facing half of the roof, the loss period was about equally long in Norrköping and Luleå, but the total loss in Norrköping was 75 kWh/m², while in Luleå it was 126 kWh/m² - 70% greater. For the roof section facing southwest, the equivalent figures were 55 kWh/m² for Norrköping and 112 kWh/m² for Luleå, i e almost the double. The southwest facing roof's period of loss was 6 weeks shorter in Norrköping than in Luleå;

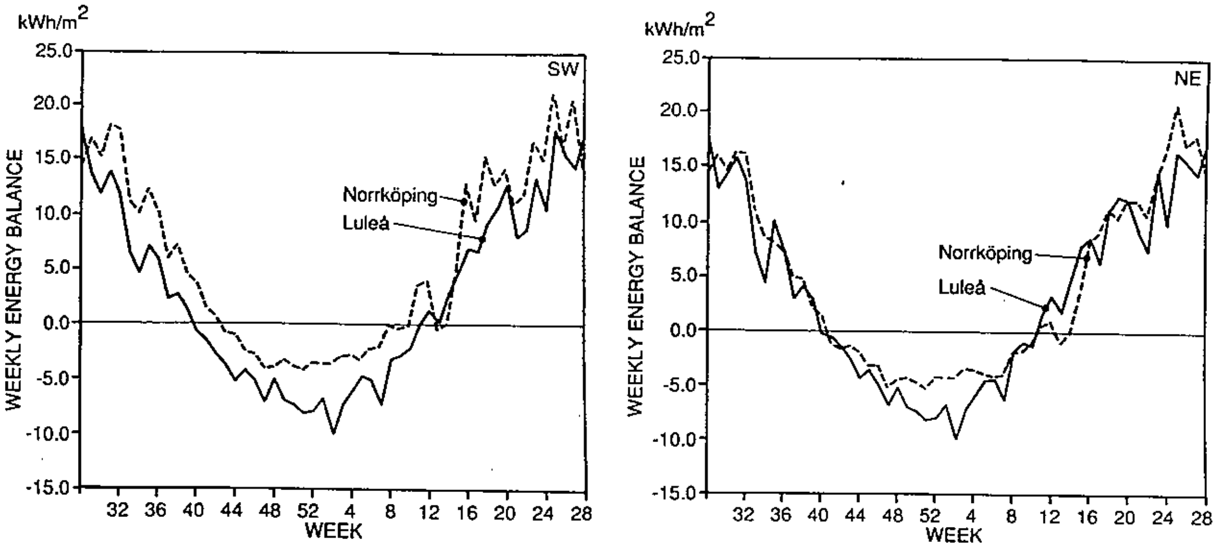


Figure 15. Simulation of the hourly energy balance of the triple pane glass roof facing northeast and southwest in two different nordic climates. Slope 30°. Weekly sums.

For the whole roof, the loss in Norrköping was 130 kWh/m²yr and in Luleå, 238 kWh/m²yr. This corresponds to a total heating demand of 230 MWh/yr in Norrköping and 430 MWh/yr i Luleå. Maybe 20-25% of these losses would occur also without the glassroof as losses through the exterior walls facing the atrium. Taken those losses away, the extra demand of energy for heating this atrium would have been some 120 kWh per year and square metre atrium floor area in Norrköping and 220 kWh/m²yr i Luleå.

The energy balance of the roof divided into indoor radiation and convection is shown in fig. 16 for the sections facing southwest. Convection losses increased with lower outdoor temperatures and reached a maximum of 2.8kWh/m² per week in Norrköping and 4.4 kWh/m² per week in Luleå. During the summer they became insignificant compared with net radiation.

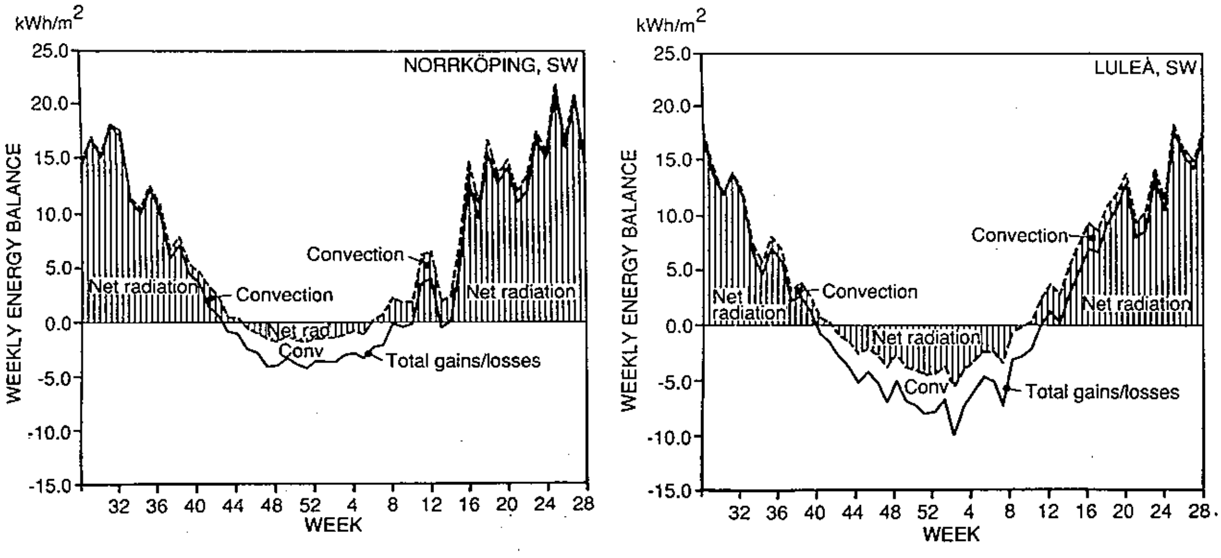


Figure 16. Simulation of the hourly energy balance of the triple pane glass roof divided into a convective and a radiative part. Slope 30°. Weekly sums.

The lowest weekly net radiation was -2.1 kWh/m^2 in Norrköping and 5.5 kWh/m^2 in Luleå. Radiation losses were thus at most more than 2.5 times as great in Luleå as in Norrköping. The reason for this is mainly that Luleå had exceedingly little solar gains during the loss period because it is situated so far north.

The U-value or "darkness U-value" was a few percent higher on the southwest side than on the northeast both in Luleå and Norrköping. Heat conduction increased slightly in accordance with the regression expression, with increased solar radiation or wind, and consequently, the U-value also rose.

During winter months the U-value lay on an average of 2.03 W/m^2K for the northeast roof in Luleå and slightly higher for the southwest roof - 2.04 W/m^2K. For Norrköping the corresponding value was 2.01 W/m^2K and 2.04 W/m^2K. Variations between the different weeks during the loss period were 7% in Luleå and 9% in Norrköping.

We can term "effective U-value" or U_{eff}, that counterpart of U-values which also includes solar heat gains, i.e. both heat which is conducted and radiated directly in divided by the difference between external and internal temperature. U_{eff} becomes positive when radiation gains are greater than convection losses. During the winter in Luleå U_{eff} lay near U even on the southwest side whereas in Norrköping it was about 70-80% of U.

We can also compare our roof with a vertical window of the same construction in the same position if we assume that it is exposed to the same wind. With the corresponding calculations we found that the radiation losses from the glass roof were 25% greater than for the corresponding vertical glazing in Norrköping and 16% greater in Luleå.

The U-value during the loss season is on average 5% lower for the window than for the roof in Luleå and 6% lower in Norrköping, fig. 17. The smaller losses from the window were due to smaller radiation losses. The difference between the northeast and southwest sides was the same for both window and roof. The roof and the window have an equal average U-value, regardless of geographical location.

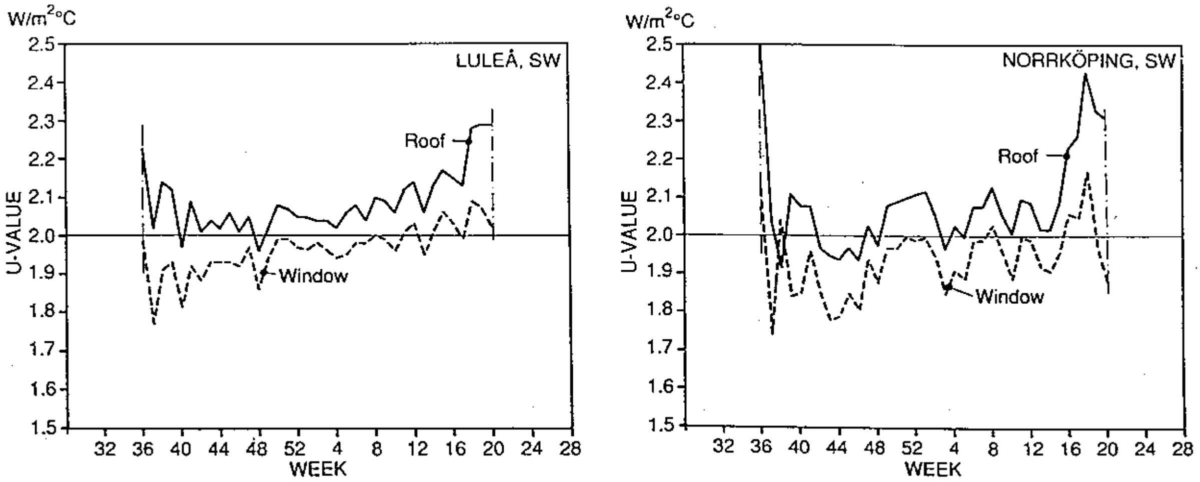


Figure 17. Average weekly effective U-value of the triple pane glass roof calculated on hourly simulations. Slope 30°.

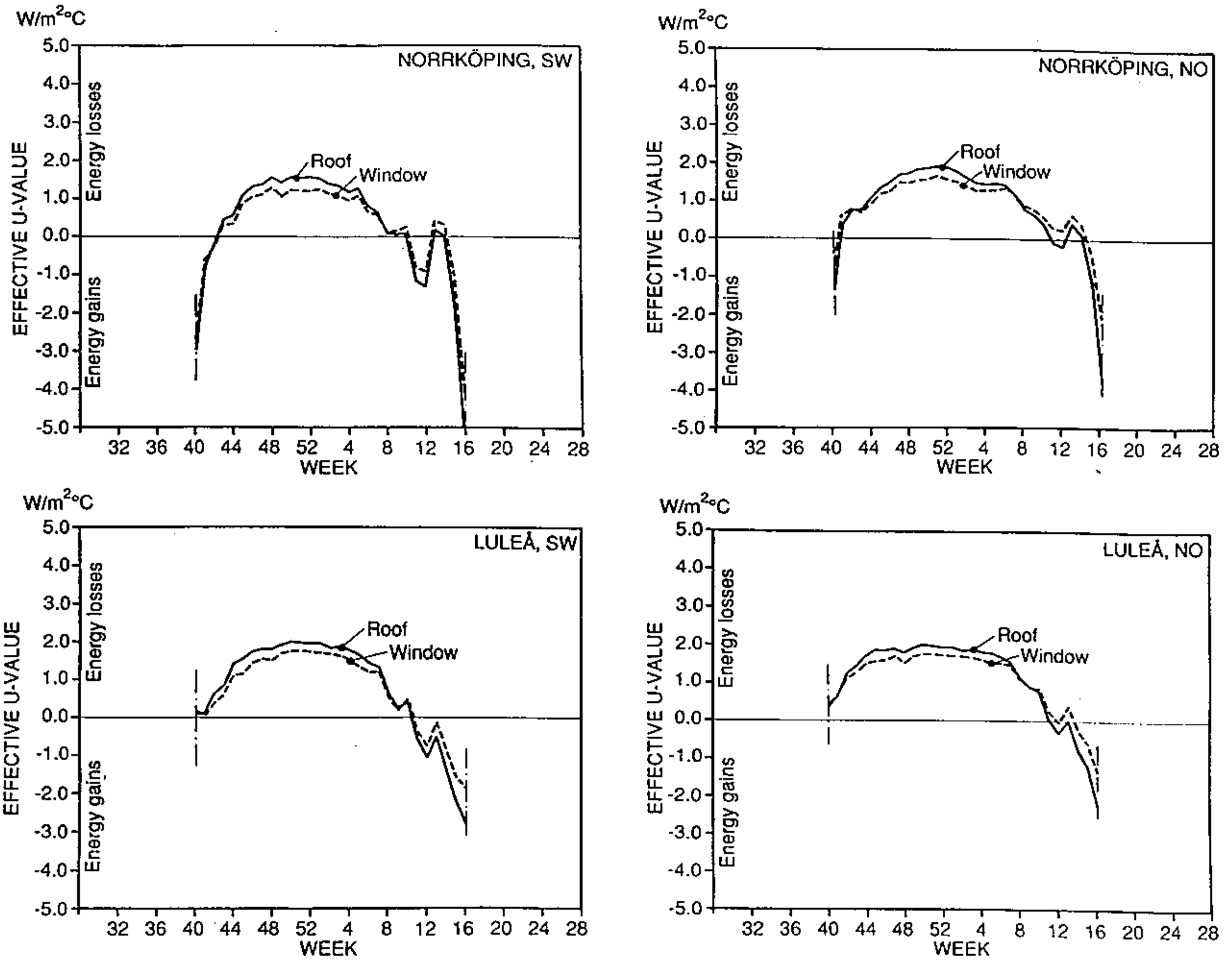


Figure 18. Comparison between the average weekly effective U-value of the triple pane glassroof and a corresponding window in different climates.

The effective U-values, U_{eff}, show that the window facing southwest was more effective as regards energy during the entire loss period than was the glass roof in either city, fig. 18. The window on the northeast side was more energy efficient than the roof during more than 2/3 of the loss period, fig. 19.

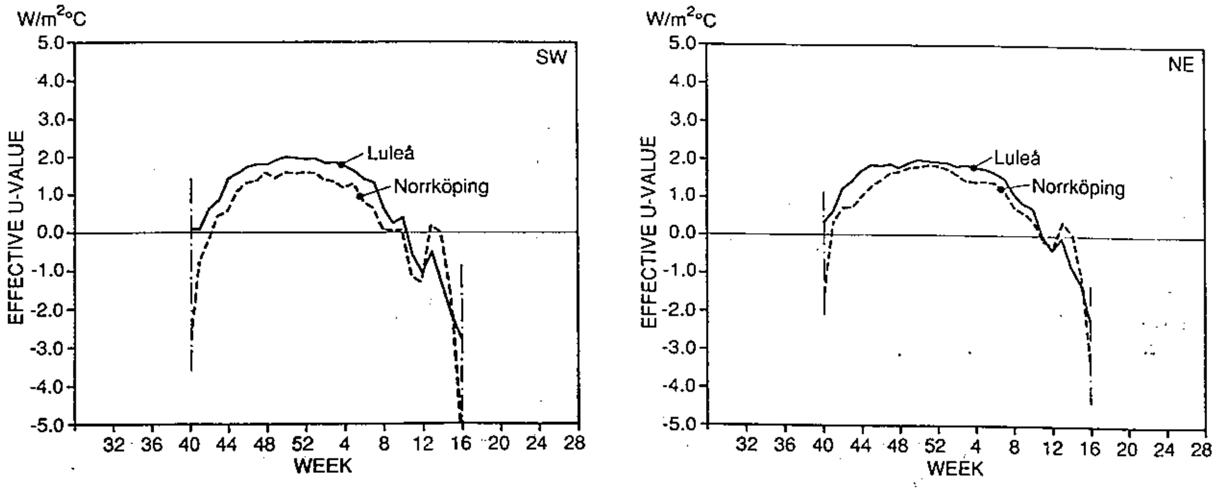


Figure 19. Comparison between the average weekly effective U-value of the triple pane glassroof in different nordic climates.

Discussion

Measurement results apply to a special building and simulations, to a particular year. Thus it may be asked how general they are.

We must first consider the accuracy of the measured results. What determines them is primarily net radiation and surface temperatures from which we have calculated the heat conduction. The net radiation should give errors up to +-9% according to Halldin, who has made a comparative study of net radiation meters (personal communication). Surface temperatures which determine heat conduction could have possibly given measurement errors within +-1°C including shelter correction during the day, but probably less at night - in which case, it involves error on less than +-10% of the heat flow. The difference between indoor and outdoor temperatures could possibly be of the order of +-0.5°C. Although measurement errors may have been rather large there is no evidence of any systematic bias. This means that terms in the regression equations are weighted correct relative to each other.

The regression method entails that the coefficients only applied to the preconditions under study, i.e. a triple-pane glass construction under winter conditions in central Sweden. However, the weather was so changeable during the measurement period that it should be possible to apply the method to relative comparisons in winter, even in other places where the climate corresponds to that of northern Europe.

U-values were less accurate during spring and autumn than winter. Since one divides the temperature difference between inside and outside, an error acquires a relatively large significance when the temperature difference diminishes. However, U-values are normally uninteresting other than in heating periods; hence we excluded them between weeks 20 and 36. But even during odd sunny winter hours the calculated U-value might have had up to 25% error since accuracy in the calculated indoor temperature was about +-2°C (compare fig. 7). The calculated U-values however were very similar for Norrköping and Luleå during the winter, despite major differences in solar irradiation.

CONCLUTIONS/RECOMMENDATIONS

The heat losses from the glass roof of an atrium are larger than indicated by the nominal U-value of the glazing. For the investigated 30° sloping glass roof, the U-value during the loss period was on average 5-6% greater than for a corresponding vertical glazing (window). This could be explained by the greater radiative losses going along with greater viewfactor to the sky of the sloping glazing. But it is generally difficult to apply U-values to atriums as the inside temperatures vary so much with solar radiation.

Wind was shown to have had little effect on the heat flow through the glazing. However, it did counteract rising heat losses during clear nights through carrying heat from the air to the emitting glass surface. And wind indirectly contributed to increasing heat losses due to increased infiltration around the roof shutters.

Calculations have shown that heated atriums' energy losses increase heavily the farther north they are. The loss periods in Norrköping and Luleå, ca 800 km farther north, were about the same - 22-24 weeks - but energy losses from the glass roof in Luleå were about double those in Norrköping. The farther south the glass roof the less the south-facing section loses in relation to the north-facing - some 10% less in Luleå and almost 30% less in Norrköping. The vertical glazing had a more positive energy balance than the sloping roof during the entire loss period for glazing facing northeast, and for more than 2/3 of the period in the case of the glazing facing southwest. If possible, north-facing glass roofs should be avoided or minimised, and the slope should be as steep as possible the farther north the atrium is situated.

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LIVING IN A GLASS HOUSE
Residents' Views - Design Recommendations

PROBLEMS UNDER INVESTIGATION AND METHOD USED

Questions

Most atriums that have been built in residential blocks have been meant to to have the double function of being a suntrap and providing a warm common area for the tenants - a zone between the dwelling and the world outside where children can play and neighbours can get to know one another. Serving the purpose of being a suntrap means they are not heated. Investigations in non heated atriums in blocks of flats with suburban surroundings show that the atrium often gets too warm in the summer and too cold in the winter, and rooms inside the atrium get very poor daylighting. Most people prefer going out to staying in the atrium, and atriums have not proved to promote contact between neighbours. Still atriums are appreciated by the tenants, (Hammer, 1984, Norrby-Herdenfeldt, 1989).

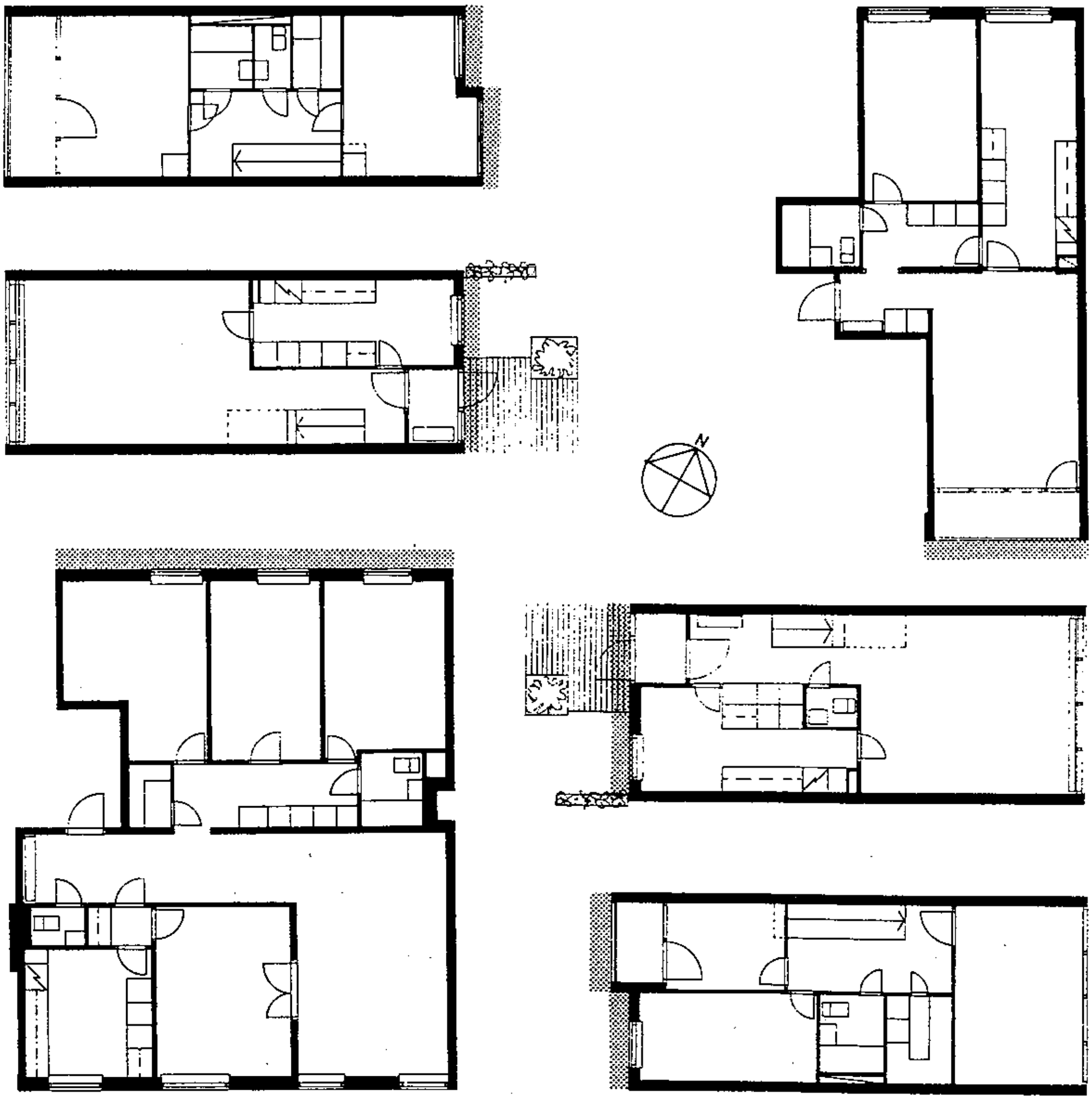
The very central position, the heated winter garden and the mixture of dwellings, offices and shops make Wasa City a very unusual glass house. Using the residents' experiences as a point of departure we wanted to discuss advantages and disadvantages with the atrium and compare with results from other atrium studies. Most tenants lived in the house before it was rebuilt, so they can compare before and after. Wasa City is unique, but it is likely that similar projects will crop up in the wave of over-glazing that at present is occurring in Swedish city centres. However, the questions in our investigation also involve general considerations as regards atriums in residential blocks.

* The quarter is surrounded by traffic noise and emissions. Can the atrium, which is a real wintergarden, heated to comfortable summer temperatures year round, in this situation compensate for lacks in the surrounding external environment? Dwellings share the atrium with offices and commercial enterprises; what are the advantages and disadvantages of this for the residents?

* The design of the dwellings has not been adapted whatsoever to the re-building. In Wasa City, balconies as well as bedrooms, living rooms and kitchens face the atrium. What difficulties or inconveniences has this caused as regards sun and daylight, noise, airing, privacy and views outside the residences? How has the lack of adaptation affected use of the dwelling?

* Half of the dwellings have fairly large separate private patio spaces in the atrium. How are they used? Have they any relevance for contacts between neighbours? A comparison can be made with the other half of the dwellings which lack private external space. Has contact between neighbours been influenced by the glazed-over roof? What are the views of those who lived in Wasa City before the retrofit?

View out from bedroom in 4 bedroom apartment.



The four main types of dwellings. The wall facing the atrium is marked.

Construction and Distribution of the Questionnaire

We sent a questionnaire to all households in the 44 dwellings that had more than one room and kitchen and that were used as residences. The content of the questionnaire was individually devised for each dwelling type. Most of the questions were multiple choice, with space provided for comments by the respondents. We received a total of 38 completed questionnaires, and we deem the response rate as satisfactory for our purpose. We also conducted formal and informal interviews with several residents and key people.

Table 1 *Compilation of response rate, household size, age respondent, time for moving in (before or after retrofit) with respect to dwelling size (number of bedrooms/diningroom) and type (apartment or maisonette)*

Dwelling size	Response rate	Household size				Age of respondent					Moved in b/a retrofit	
		1	2	3	4	-34	35-44	45-54	55-64	65-	before	after
1 bed apt	6/6	4	2					1	1	4	5	1
2 bed mai	10/13	4	2	3	1	4		2		4	6	4
3 bed mai	12/12		8	4		1	2	4	3	2	10	2
3 bed apt	2/2		2					1		1	2	
3 b+d apt	8/10	1	6		1		1	2	2	3	7	1
	38/44	9	20	7	2	5	3	10	6	14	30	8

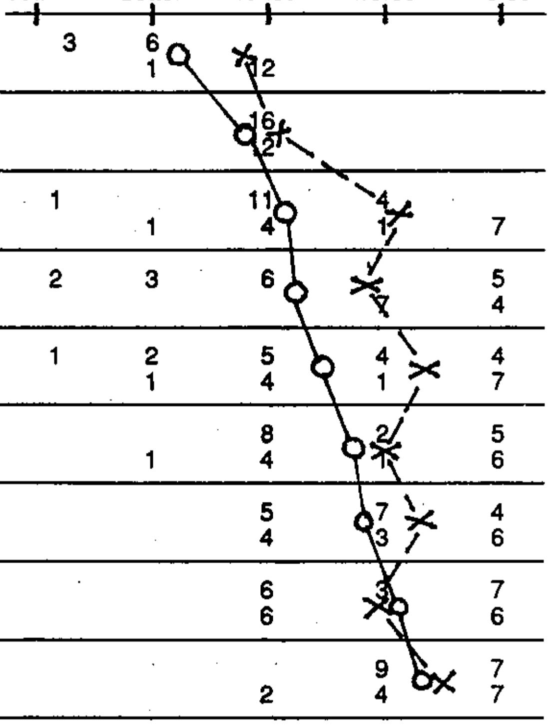
RESULTS AND ANALYSIS

Positive and Negative Responses to the Atrium

According to those who lived in the house prior to the retrofit, what changes has the re-building brought about? On average, only contact between neighbours has been considered to have improved, and only by maisonette tenants - 9 out of 16 maisonette households who lived in the house before the retrofit think neighbour contacts have improved. According to the average assessment, all other conditions mentioned in the questionnaire have worsened, particularly daylight.

"What are the three worst drawbacks with the atrium?" Responses to this open question from both maisonette and apartment residents cited first and foremost bad air and less satisfactory airing possibilities - cooking odours from the courtyard and difficulties in airing out rooms, clothes and bed linen. Secondly, less day lighting was mentioned, and in a few cases, less sunlight, inside the dwellings and on the patios or balconies, as well as having less of a view from the dwellings. Thirdly, complaints were made about noise from the atrium, especially from the automatic roof hatches. In general, the disadvantages have primarily to do with effects of the glazed-over roof on the climate in the dwellings.

Table 2 *Questions to those who lived in the house beore the retrofit: What changes do you think the atrium has brought about?*



		Much better	Slightly better	No difference	Slightly worse	Much worse	Internal response rate
Contact with neighbours	maisonettes	3	6				16/16
	appartments		1	12			13/13
View in	maisonettes			16			16/16
	appartments			12			12/13
View out	maisonettes	1		11	4		16/16
	appartments		1	4	1	7	13/13
Plant growing	maisonettes	2	3	6		5	16/16
	appartments				7	4	11/13
Air temperature	maisonettes	1	2	5	4	4	16/16
	appartments		1	4	1	7	13/13
Noise from atrium	maisonettes			8	2	5	15/16
	appartments		1	4	1	6	12/13
Sunlighting	maisonettes			5	7	4	16/16
	appartments			4	3	6	13/13
Smell from atrium	maisonettes			6	3	7	16/16
	appartments			6		6	12/13
Daylighting	maisonettes				9	7	16/16
	appartments			2	4	7	13/13

—O— *Mean value, maisonettes*
– X — *Mean value, appartments*

The greatest advantage mentioned by the maisonette tenants is having a weather-protected outside space, where one can sit year round, especially in winter. Secondly, many aptreciate not having to deal with rain and shovelling snow. Thirdly, especially the newly arrived maisonette dwellers appreciate their views and the plantations and like their "unusual" courtyard. The apartment dwellers mentioned hardly any advantages. The comments formulated by the tenants themselves were most often negative and were largely about the design of the atrium. Several apartment dwellers, for example, thought that the design is "plastic" and that the courtyard is "all show without function".

Table 3 *What is your overall impression of the atrium?*

	Mainly good	Mainly bad	Own answer either or	Internal response rate
Maisonettes	15	6		21/22
Apartments	4	7	2	13/16
Moved in before retrofit	14	12	2	28/29
Moved in after retrofit	5	1		6/9

What is positive has been more difficult to discover and express than what is negative. The majority of tenants, however, have a positive overall impression of the atrium due to the responses of the tenants who have recently moved in.

Internal Climate in the Atrium

According to the measurements and calculations made in the atrium and in a model room in the courtyard in Wasa City, daylight is reduced by about half in those rooms placed under the glazed-over roof - kitchens and bedrooms in the maisonettes and either bedrooms or living rooms in the apartments. Sunlight has also been affected by shadows from the roof construction, overhead cranes for cleaning and the automatic roof shutters. Nearly all the maisonette dwellers spontaneously commented on the reduced daylight, especially in their kitchens where they suffered particular inconvenience. In response to a direct question, it was thought that generally all rooms located under the glazed-over roof had insufficient daylight. Significantly fewer thought that sunlight in the equivalent rooms was inadequate, and those who did consider their access to sunlight inadequate were almost all maisonette dwellers with their kitchen windows facing east.

Apartment dwellers on the north side of the courtyard, with enclosed balconies and living rooms were particularly dissatisfied with these arrangements - especially as regards access to sunlight and daylight, but also as regards the loss of "fresh air". There were many complaints about the lack of airing possibilities and bad air, especially in rooms facing the courtyard, but also in rooms facing the street. Ventilation shutters in the glass roof have not functioned properly and in summer it has become much too warm in the courtyard, which of course has affected temperatures - and airing possibilities - in the rooms inside the courtyard. Half of the tenants complained of too high temperatures in the atrium in summer; none has remarked on the temperatures during the winter.

Rooms badly affected by noise lie to the same extent facing the courtyard as facing the street. During the summer the ventilation shutters in the roof cause noise. In winter, snow on the roof makes noise as it slides down the glass in great chunks. Also the wooden duckboards in the open spaces in the atrium were mentioned as a source of noise. Noise is intensified in the atrium.

In a quarter of the cases the glazed-over roof has caused changes in use of rooms. In several maisonettes, the occupants have moved their bedrooms from the courtyard side to the street side because of airing problems and/or bad climate in general. Apartments with allt the bedrooms facing the courtyard do not have this option. Many have moved their houseplants to rooms facing the street, and several mentioned they use the rooms facing the courtyard less because they have become darker.

Use of the Atrium

Despite complaints from the residents about noise and odours from the restaurant and shops and despite the fact that they hardly use the commercial amenities, almost all the respondents thought that the activities on the ground floor of the atrium was stimulating.

Table 4 *How often do you use shops etc in the atrium?*

	Almost dayly	Once a week	Once a month	Never a year		Internal response rate
Eat in restaurant	1	3	5	8	18	35/38
Shopping	5	13	12	3		33/38
Passing through	6	8	14	2	1	31/38
Sitting on benches			1	2	29	32/38

Table 5 *How often do you use your patio?*
(Only maisonettes)

	Almost dayly	Once a week	Once a month	Once a year	Never	Internal response rate
During summer	4	8			9	22/22
During winter	5	10	1	4	2	22/22

The patios in the atrium are utilised for drinking coffee and having chats - presumably with neighbours. In the summer they are little used compared with real outdoor patios, but over a whole year, their use becomes fairly significant. No resident mentioned wanting a larger patio, but many expressed a wish for more privacy, preferably screening off with plants.

Half of the maisonettes have balconies under the glass roof and half facing the street. All face west. The balconies facing the street are used for sunbathing in summer and airing in winter. The balconies under the glass roof are used for drinking coffee year round. Half of those with balconies facing the street used them once a week or more often during the summer, which is very seldom compared with results from other studies of residential blocks (Engvall 1989, Westerberg 1990). In the present study the balcony was deemed in many cases to be unusable. Those residents with balconies facing the street often wanted them glazed-in and those whose balconies faced the atrium wanted them outside.

Contacts with Neighbours

The architect of the retrofit claimed that contacts between neighbours increased during the re-building process, largely because of several information meetings which stimulated lively discussions for and against the retrofit. This sounds plausible, yet two-thirds of the households have said that there is no difference in contacts between neighbours between before and after the retrofit. However, there are substantial differences in responses from those living in apartments and those in maisonettes. Most of the maisonette dwellers believe that contacts with neighbours have improved after the retrofit. Thus it would seem that the physical changes per se - the weather-protected patios - have had a greater positive value as regards contacts between neighbours than the rebuilding process.

Table 6 *How often do you meet with neighbours?*

	Almost dayly	Once a week	Once a month	Once a year	Never	Internal response rate
Maisonettes	5	4		4	1	20/22
Apartments		1		3	11	15/16
Moved in before	5	4		5	14	28/29
Moved in after	1		2	4	7/9	
Single person	2			2	4	8/10
Couple		4		4	11	19/20
More than two	3	2		1	3	9/9
	5	6		7	18	35/38

One of the questions concerning social contacts was about frequency - how often the respondent had dinner guests, overnight guests, had visits from children, grandchildren and other relatives, how often he or she met neighbours and friends. On the whole maisonette dwellers showed higher contact frequencies, but large differences arose as regards contacts with neighbours. Contacts with friends and relations were more or less equal for all respondents. Single person and multi-person households meet neighbours somewhat more often than two-person households. Length of residence, i.e. whether the respondent moved in before or after the retrofit, also is significant, but not more than the type of dwelling. Frequency of contacts with neighbours has also a positive connection with a positive overall impression. Patios have contributed to a positive interaction between neighbours.

DISCUSSION AND CONCLUSIONS

How Can Climate Problems Be Minimised in the Residential Space inside the Atrium?

Atriums in residential blocks with more than two storeys have generally been designed as some sort of balcony-access block. According to Swedish building regulations and practice only the kitchen is placed facing the balcony-access if the latter is a passage to another apartment. The reason for this is primarily that views into rooms in private dwellings other than the kitchen should not be admissible. This has meant that it is difficult to place apartments larger than two rooms plus kitchen along a balcony-access, and the same applies if the balcony-access lies in an atrium.

However, is it actually suitable to place a kitchen along a balcony-access in an atrium? The balcony-access cuts off a great deal of daylight, glazing-over requires small distances between houses which means further reduction of light and the glass roof additionally cuts all daylight to just less than half. Moreover, it is common that people try to create more privacy by hanging curtains in the windows, especially in the lower panes where most of the daylight comes in. Fear of lack of privacy can thus lead to further reductions in daylighting in a balcony-access block. The sum of all this means that rooms facing a balcony-access in an atrium are extra dark, and daylight is first and foremost needed in the kitchen.

In Wasa City there are no balcony-accesses that block light from windows. Even so, the residents consider the reduction of daylight in their kitchens a great drawback. The kitchen window could however have been much larger since the courtyard is heated and consequently one does not have to reckon with loss of energy. The working areas in the kitchen also could have been positioned differently and not several meters from the window. The room could have been shallow instead of deep and had better visual contacts with other daylit rooms - which would have made it lighter. In a newly built, well-planned building with an atrium - like Wasa City - daylight conditions in the kitchen could have been significantly better and the residents would not have been able to make comparisons which can only be critical of the retrofit's solution to natural interior lighting.

No one in Wasa City is bothered by others being able to look into private rooms. In the maisonettes the patios maintain a suitable distance as regards passage along the deck. Bedrooms lie on the floor above the deck. Two-floor apartments are advantageous from the point of view of both privacy and daylight even in buildings with more than two storeys since there are double ceiling heights between balcony-accesses. If the kitchen was placed on the lower floor and bedrooms on the upper - as in maisonettes in Wasa City - then the kitchen and patio would have better access to sun and daylight and the bedrooms, more privacy. (It should be mentioned that at present in Sweden, building two-storey apartments in residential blocks is not common, especially not in balcony-access blocks.)

In Wasa City, all those living in apartments with bedrooms facing the courtyard are dissatisfied with airing facilities. In the maisonettes, there are bedrooms facing both the street and the courtyard, and those tenants dissatisfied with either have been able to change their rooms - which some have done. In larger apartments, especially in smaller households, there are more possibilities of adapting dwelling use according to circumstances. Hence, a bedroom can be placed facing the atrium in larger apartments where there is also a bedroom facing the street, which can receive fresh air.

Wasa City tenants who have their living room and balcony facing the atrium complain volubly about lack of sun and daylight and about not being able to air the room properly. It is hardly suitable to place the living room towards an atrium when there is no window letting in fresh air. One should be able to have houseplants in a living room where the visual environment is especially important.

Heated atriums make large windows viable, and this would reduce problems with daylight. In balcony-access blocks, two-storey apartments offer better prerequisites for satisfactory sun and daylighting and less problems of privacy than do ordinary, single-level apartments.

How Should an Atrium Be Designed In Order To Promote Contacts Between Neighbours?

Several studies have shown that contacts between neighbours are more lively in areas with detached houses than in those comprised of multi-family dwellings, (i.e. Hjärne, 1985). This is because of differences in the composition of the households, forms of tenure, mobility, etc., in addition to the physical environment. In multi-family residential areas, the movements of adults tend to be limited to communication to and from the dwelling. Our for the most part cold climate and lack of activities that can keep adults warm have, as has been mentioned early, a constricting effect on social life outside one's own dwelling. The private bit of land outside the door of a detached house gives the occupant the opportunity to see and be seen by his or her neighbours - when shovelling snow, tending the garden, drinking coffee, etc. This compared with the landings and perhaps a bench outside the entry to a residential block. In Wasa City, those with patios facing the atrium have more contact with their neighbours than those without patios.

Contacts with neighbours can also be conflicts with neighbours, which is one reason why most people (at least in Sweden) are rather reserved, prepared to retreat before they have become acquainted with their neighbours. A patio is thus an ideal facility for gradual acquaintanceship, as on one's patio one decides oneself whether to talk to the neighbour.

In commonly shared outdoor areas in residential areas many people feel abandoned and exposed. They do not want others to think they are seeking contacts. This is especially true of people living on their own - no one wants to appear alone, particularly if he or she is. Several studies, among them one made of an atrium in a multi-family block, have shown that people living on their own use common areas least, (Norrby-Herdenfeldt, 1989). The single person households in Wasa City and elsewhere are to a great extent elderly and more housebound, and thus can especially enjoy a weather-protected patio that needs no looking after. Our study of Wasa City reveals that the atrium was used more by those living alone than by couples.

It is unfortunate that quality differences between apartments and maisonettes in Wasa City are so great as regards the atrium. One apartment dweller wished to have a commonly furnished patio area in the atrium, but it is hardly likely that many apartment dwellers would make use of it. However, maisonette dwellers definitely would: they know each other better and have their own dwelling within reach - "street parties" have occurred on the short side of the deck. That space exists has been enough to stimulate such activities.

In Wasa City the stairs are separated from the atrium. This is an advantage, taking noise, and the tenants' security and privacy into consideration. At least after closing hours, it is an advantage to distinguish between dwellings and commercial activities. However, it is also a disadvantage since stairs are a natural meeting place for the residents. If the stairs were located in the atrium the tenants would have better contact with the activities going on on the ground floor.

A commonly-shared area outside the residential area is a good idea, but first, make private patio-type areas outside all the dwellings.

When Is an Atrium in a Residential Block Suitable?

The tenants who lived in the building prior to the retrofit were considerably more negative to the changes than those arriving afterwards. This can be due to difficulties experienced during the re-building. Many tenants had expressed their views concerning the building plans which were never acknowledged. They can easily make before-and-after comparisons; for instance, that daylight has been reduced can only be experienced as a worsening of conditions. Had the building been new and all the tenants newly arrived, evaluations would probably have been very positive, especially those from the tenants in maisonettes.

Thus two different problems arise when a glass roof is fitted later -after occupancy - as in Wasa City. First, one should reckon that the tenants will be less satisfied - assuming the changes are not so comprehensive that a wholly new group of tenants moves in. Secondly, the negative effects in the apartments cannot be limited through appropriate design or making use of the advantages of building with simpler facade material and larger windows in the rooms. If the courtyard is heated in winter, as it is in Wasa City, in principle no heat insulation on the courtyard side is necessary, and this should provide greater freedom when designing the windows.

The heating and plantations that turn Wasa City into a winter garden have a decisive importance. The private patios in the atrium are actually used a bit more in winter. In the previously mentioned atrium studies it was found that the residents preferred to be out in " real nature" over being in the atrium, (Norrby-Herdenfeldt, 1989). The courtyard in question was unheated and the building was situated in a relatively sparsely-populated suburban environment. A few tenants in Wasa City have mentioned that they miss being able to sunbathe - either on the maisonette deck or a balcony, but many more are happy to not have to deal with rain or shovelling snow. An attractive outdoor alternative does not exist and has not existed. Wasa City's central location, with constant traffic noise and exhaust fumes, makes the atrium quieter and possibly healthier than a comparable alternative with outside balconies and maisonette decks.

The dimensions of the atrium is limited for technical and economical reasons. Small distances between buildings is a bad prerequisite for daylighting, as mentioned before. Blocks in city centres are suitable for glazing-over because the buildings must be close together anyway.

Even in residential blocks, the atrium must be a winter garden. It is a good alternative to a sterile outdoor environment, for instance in a congested city centre, and shops can share the costs for heating and plantations in the courtyard.

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IEA XI ADVANCED CASE STUDY: GATEWAY 2

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ABSTRACT

The new headquarters for paper manufacturers Wiggins Teape was completed in 1982. The brief for the building called for a low budget development with the provision of natural ventilation as opposed to air conditioning. These requirements led to the offices being planned around a central atrium. In the summer, ventilation and cooling of the offices was to be achieved by solar gain creating a stack effect in the atrium and drawing air through the offices via linking windows. In the winter, perimeter underfloor heating in the atrium was to be used to reduce cold down draughts and induce ventilation in the offices. A series of tests were undertaken to validate the design intent. It was found that in the summer, the ventilation strategy worked, although it seemed that the major influence on moderating the internal climate was the high thermal mass of the structure. In the winter, it was found that the air movement was not as intended. Overall ventilation rates during the day were often only just adequate, resulting in fairly high concentrations of carbon dioxide being recorded in the offices.

1. INTRODUCTION

The new headquarters for paper manufacturers Wiggins Teape was completed in 1982. The brief for the building called for a low budget development which complemented their existing adjacent building, and the provision of natural ventilation to the offices as opposed to air conditioning. These requirements and certain site constraints lead to the offices being planned around a central courtyard. The attractions of glazing over the courtyard to form an atrium soon become apparent, both for its amenity value and potential energy saving. It was concluded that natural ventilation for the building would be improved by the presence of the atrium, and controllable by means of openable roof vents.

The building is currently being subjected to an "Energy Performance Assessment" on behalf of the Energy Technology Support Unit for the Department of Energy. This is considering other aspects of the performance of the building as well as the passive solar features such as energy used for space heating and lighting.

2. BUILDING DESCRIPTION

2.1 Form

The building is rectangular in shape (based on a 7.5m grid) and has 5 floors of offices, normally 13.5m deep, surrounding the central 45m x 22.5m atrium. Below the main building there are two basement floors predominantly used for car parking and southern two storey extension housing the computer at the same level. The major axis of the building is East-West. For the purposes of this report only the offices surrounding the atrium on the top four levels are being considered, providing about 6700m^2 of accommodation. Figure 1 shows a typical floor plan.

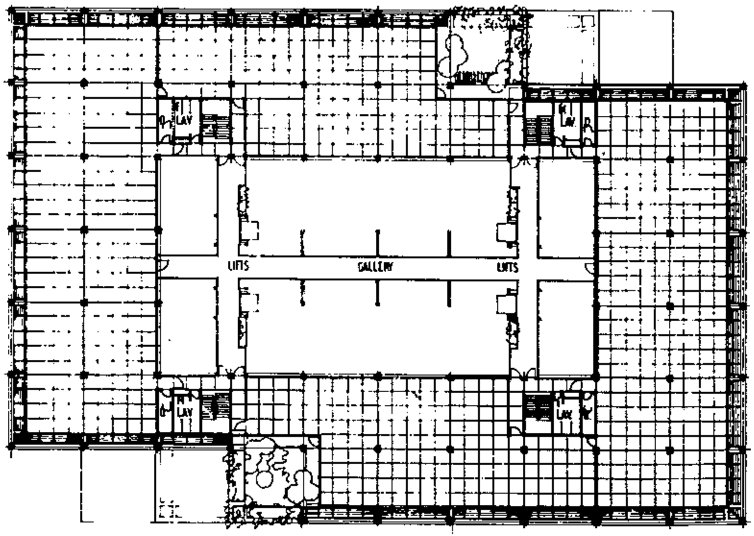


FIG 1 Typical Floor Plan

2.2 Fabric

The building has a concrete frame structure to the offices and uses a cruciform steel columns in the atrium to support the walkways and roof structure. The external walls comprise curtain walling incorporating 100mm insulation in opaque areas with single glazed opening windows. The wall between the office and atrium comprises an oak screen incorporating single glazing with manually adjustable glass louvres together with acoustically absorbent panels. At the east side of the atrium there are no offices at the top level and a single glazed clerestory is incorporated. The roof to the atrium comprises double glazed rooflights, some of which are remotely openable, and lightweight roofdeck incorporating 100mm insulation all on a steel frame. The office roof incorporates 75mm polystyrene insulation. The internal floors comprise precast concrete inverted troughs with exposed soffits incorporating light fittings and timber suspended floor above.

2.3 Function

This building is the administrative headquarters for a paper manufacturers. All of the upper floors are used as offices and include a plethora of computers, terminals and printers. The accommodation surrounding the ground floor of the atrium is predominantly used as catering and social facilities.

2.4 Services

Space heating - Three 600kw (12 x 50kw) modular gas boilers feed LPHW distribution pipework serving panel radiators under windows. Twenty sub-zones are served, each controlled by a thermostat and motorised valve. Further control is achieved by the use of thermostatic valves on each radiator. An energy management system is used for optimum start/stop control and additional temperature control. The atrium has heating coils embedded around its perimeter and these are served by waste heat from the chillers in the computer suite. There is also the facility to run this heating from the boilers.

Hot water - Two calorifiers in the main plant room are heated by the modular boilers. During the summer the waste heat from the computer suite air conditioning is used to pre heat the hot water.

Lighting - fluorescent luminaries are recessed in v-shaped troughs in the office ceilings. Groups of these are controlled by local pull cord switches. An automatic override system switches lights off at predetermined times throughout the day, they may be switched on again by the occupants.

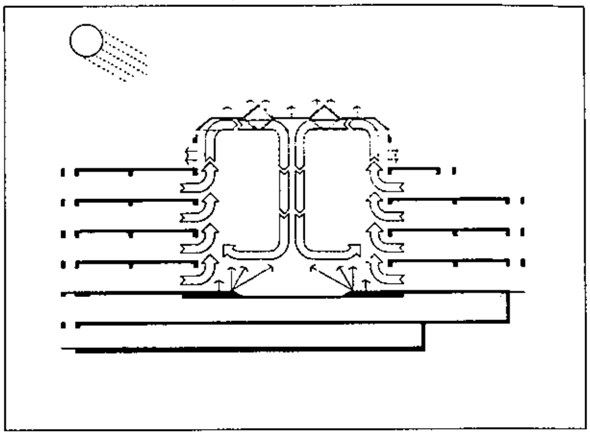
2.5 Location

The building is located in the "business zone" of the medium sized town of Basingstoke which is 75km to the WSW of London, England. The site slopes moderately to the south to which there is an open aspect. To the west there is a similar sized building about 15m away, to the north there is an open aspect, to the west there is a ten storey office building about 50m away.

2.6 Passive Solar Features

The main passive solar feature of the building is the atrium.

During the winter it provides a buffer space which reduces heat loss from the offices (compared to the originally envisaged courtyard building). The low temperature perimeter underfloor heating system tempers the environment at ground floor level and is intended to reduce cold down draughts and induce ventilation from the offices as shown in figure 2.



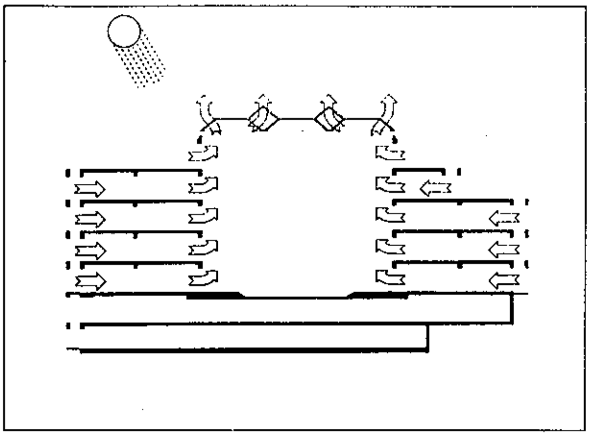


FIG 2 Air Movement: Winter **FIG 3 Air Movement: Summer**

During the summer the atrium assists with the natural ventilation and hence the cooling of the building. Solar gain through the roof lights warm the atrium and the stack effect induced, when the rooflights are opened, draws air through the offices via the external windows and louvre windows into the atrium as shown in figure 3.

3. EVALUATION LEVEL

3.1 Objective

The objective of this evaluation was to test the design intent of providing natural ventilation to the offices by using the atrium as described above. This was done by undertaking short and long term tests during the winter and summer. The short term tests were mainly concerned with attempting to visualise the air movement within the atrium and offices and between the two. The long term tests were concerned with attempting to quantify the air movement between different spaces and address amenity issues.

3.2 Experimental Design - Short Term Tests

Three methods were considered for the visualization of air movements within the atrium. These were using smoke, helium filled soap bubbles, and helium filled neutrally buoyant balloons. Previous research (1) using these three methods in a large laboratory, together with restrictions imposed by the building's owners, influenced the decision on the methodology adopted. It was decided to use small scale smoke generation for spot checks of air movement within the offices, and neutrally buoyant helium balloons in the atrium.

3.3 Experimental Design - Long Term Tests

For the longer term test it was decided that measuring the concentration of a tracer gas in a number of offices and the atrium would reveal the ventilation rates of the spaces and perhaps indicate the direction of air movement between them.

It was decided to use carbon dioxide as it was generated by the occupants and did not have to be introduced, the equipment would be able to run continuously for a long period with little or no attention, and the analyser was available and had been found to be very reliable in the past. The main disadvantages of using CO_2 as a tracer gas were that detailed knowledge would be needed about the number of occupants in a space and their metabolic rates for the computation of daytime ventilation rates and that there is a fairly high background concentration to be taken into account which can be variable. Other researchers have used this method for assessing ventilation rates, notably Penman (2).

It was decided that it was important to measure the CO_2 concentrations in a sample of offices on each elevation and at each level. Practicalities of installing the equipment led to all of the offices on the north elevation being monitored and all of the offices on level 5, giving seven sampling points. In the atrium it was decided that concentrations should be measured at a number of locations, these were above the high level catwalk, centrally at level 5, and at each end of the atrium at level 3. The external concentration of CO_2 was also measured.

The analysis of the CO_2 concentrations in the offices and atrium to provide information on ventilation rates and air movement was addressed at varying degrees of complexity. Some of the analysis concentrated on assessing the ventilation rate overnight for the whole building. This was achieved by using the well known decay equation as follows:

$$Cav(t) - Ce(t) = [Cav(0) - Ce(0)]*e^{-nt}$$

Where: Cav = av concentration of CO_2 in building (at time t)
Ce = external concentration of CO_2 (at time t)
n = ventilation rate, air changes/hr
t = time

Plotting ln(Cav - Ce) against time give a straight line graph with a slope of n.

Some other simple analysis was undertaken to assess the ventilation rate of the whole building during the daytime. This was also based on the continuity equation:-

$$V*\frac{dCav(t)}{dt} = M(t) - Qav*[Cav(t) - Ce(t)]$$

Where: V = Volume of the building
Qav = Ventilation rate for whole building
M = Production rate of CO_2 in building

Now under steady state conditions, i.e. no variation in the level of CO_2 in the building

$$Qav = \frac{M}{Cav - Ce}$$

or

$$n = \frac{M}{V*[Cav - Ce]}$$

There is insufficient space in this report to go into the next stage of analysis.

It was also decided to measure temperatures at different levels within the atrium and in the offices being monitored for carbon dioxide levels. These were to be used for qualitative purposes.

4. MEASUREMENTS

4.1 Winter Visualisation Tests

4.1.1 Method

It was hoped to carry out the winter visualisation tests on a cold, cloudy still day at a weekend. Unfortunately the winter of 1989/1990 was much warmer than average and particulary windy during January and February so a compromise had to be made. The tests were carried out on Saturday 10 February 1990 and the external temperature was 7.3°C mid morning and 11.0°C mid afternoon. The wind was from the south west throughout the day and increased from an average of 1.5m/s mid morning to 4m/s mid afternoon. The morning was cloudy and dull with continuous moderate rain which eased off toward midday. There were sunny periods during the afternoon.

About 15 people were working in the building during the morning, consequently there were few lights or items of electrical equipment turned on in the offices. The heating to the offices was turned off. The perimeter heating to the atrium was turned on with a heat output measured at around 20kw throughout the day.

As the building was to be tested in "winter mode" it was checked that rooflights and external windows were closed and that the louvres between the offices and atrium were open. Remedial action was taken as necessary. Where private offices faced either the atrium or the external windows, the entrance doors were left open except when locked (which also meant some louvre windows remained closed).

About twenty plasticised foil balloons were partially filled with a helium-air mixture. They were heat sealed and then left to acclimatise to room temperature for a quarter of an hour. They were then balanced to a neutral buoyancy using self adhesive tape. Immediately before being released in the atrium each balloon was rebalanced.

Balloons were released individually 1.5m from floor level at a number of positions from the atrium floor. Two balloons were also released above the high level catwalk. The movement of each balloon was recorded using a video camera positioned on one of the walkways, and plotted on a plan and elevation of the atrium. A stopwatch was used to time balloon movement between floors.

Smoke tests using incense sticks were undertaken in the atrium to confirm air movement observed during the balloon tests. A hot wire anemometer was also used to try and quantify any air movement observed.

Another series of smoke/anemometer tests were also carried out in the offices. These concentrated on detecting air movement in the centre of the offices and through the louvre windows. These tests were carried out on level 5 and 7.

4.1.2 Findings

The results of the balloons tests can be summarized as follows:-

- The air movement in the lower regions of the atrium was predominantly from east to west.
- The air movement observed at high level in the atrium was from west to east as was confirmed by releasing balloons from the maintenance catwalk beneath the rooflights.
- All balloons released rose eventually indicating a general vertical air flow throughout most of the atrium, the vertical velocities observed did not appear to have a pattern.
- Several balloons were observed to descend at the eastern end of the atrium.

As the air movement observed was predominantly on the east-west axis it was possible to characterise it on a section of the atrium. An approximation of the air movements observed about 2m from the south and north faces of the atrium are shown in figures 4 and 5.

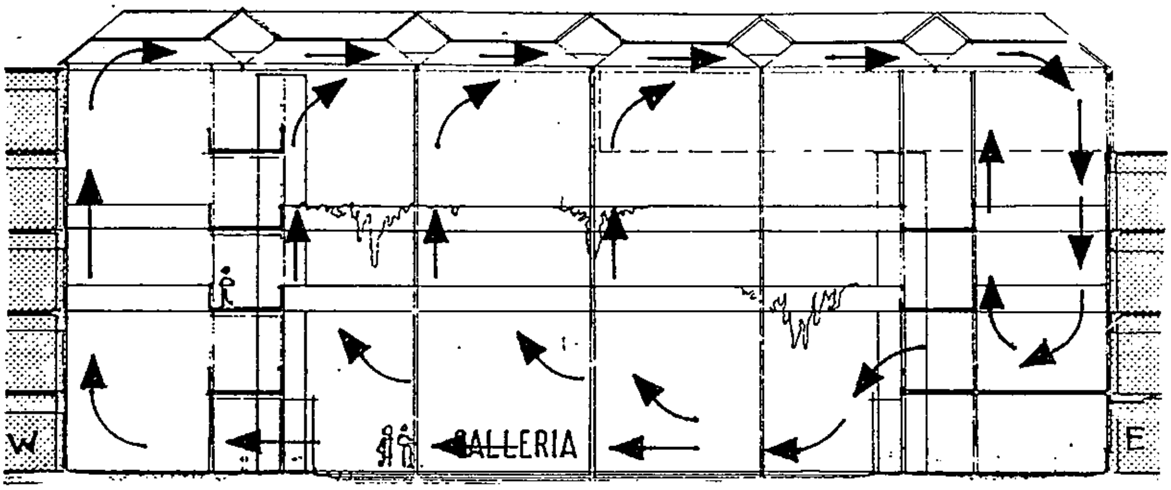


FIG 4 **Air movement adjacent to the south face of the Atrium (looking north).**

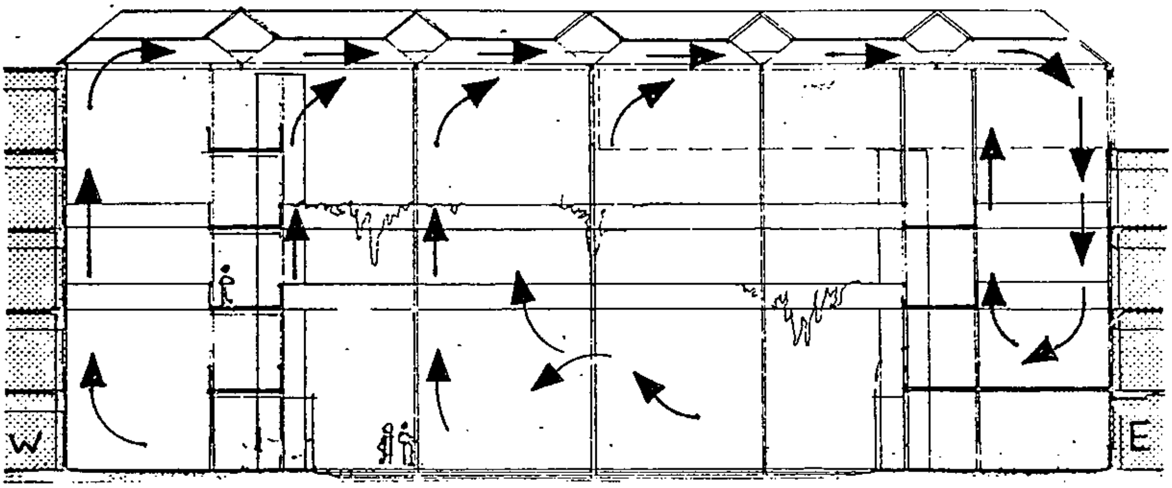


FIG 5 **Air movement adjacent to the north face of the atrium (looking north)**

At level 7 in the atrium, the smoke tests confirmed the upward air movement observed during the balloon tests, similar speeds of 0.15 to 0.3ms/1 were also recorded. There was however, little or no air movement observed within the offices on this level.

At level 5 smoke tests could be undertaken over the length of the atrium. The results from these tests confirmed the observations made about the balloon movements, in particular the downward air motion especially at the atrium facade.

There was little or no air movement detected within the offices on level 5. Air flow through the louvre windows, from the offices into the atrium, as per the design strategy, was only observed consistently at the western end of the north facade.

Movement was from atrium to offices at the eastern end of the building. Elsewhere little or no air movement was obseved. Interestingly these flows from the atrium into the offices coincided with the downward flows at the atrium facade.

Immediately before the balloon tests commenced a significant draught was noticed running from east to west across the atrium floor. The Assistant Building Services Manager had previously mentioned that he had often noticed this draught and assume that it came from the loading bay doors on level 2 via the stair wells or lift shaft. The loading bay doors were found to be closed. Test were carried out using smoke from an incense stick, and no significant air movement was observed from the staircases in the north east and south east corners, the restaurant or from the lift shaft.

4.2 Winter Long Term Tests

4.2.1 Method

In order to further investigate the air movement and exchange within the building, various items of equipment were installed in mid February 1990. These included the following:

- Fourteen stand alone temperature recorders were placed around the atrium at levels 3, 5, 7 and 8. They were set to record temperatures every half an hour.

- Stand alone temperature recorders were positioned centrally in the north, south, east and west offices on level 5 and the north offices on levels 6 and 7.

- A multi-point sampling Carbon Dioxide analyzer was installed in the atrium collecting samples via plastic tubing from various offices, the atrium, and external air. The carbon dioxide concentrations for each location were sampled and logged every 15 minutes. The sampler was recalibrated weekly for the duration of the tests.

- Equipment was installed on the roof to measure external temperature and horizontal solar radiation every 15 minutes.

All of this equipment was left running until early April 1990 in order to obtain data for a range of different weather conditions. Unfortunately the weather remained much warmer, sunnier and more windy than average throughout this period.

Other information it had been hoped to collect, but resources did not allow, included the following:-

- detailed observations of the number of people working within the offices being monitored for CO2 levels throughout the working day.

- accurate knowledge of the occupants metabolic rates.

- detailed observations of external window opening, louvre window status, and rooflight opening.

For the analysis, if was decided to concentrate on the two weeks of data which corresponded to the period of best capture of data and some of the cooler temperatures of the period. This period was from 26 February 1990 to 11 March 1990.

4.2.2 Findings

The weather during the two week period used for analysis is shown in figure 6 below.

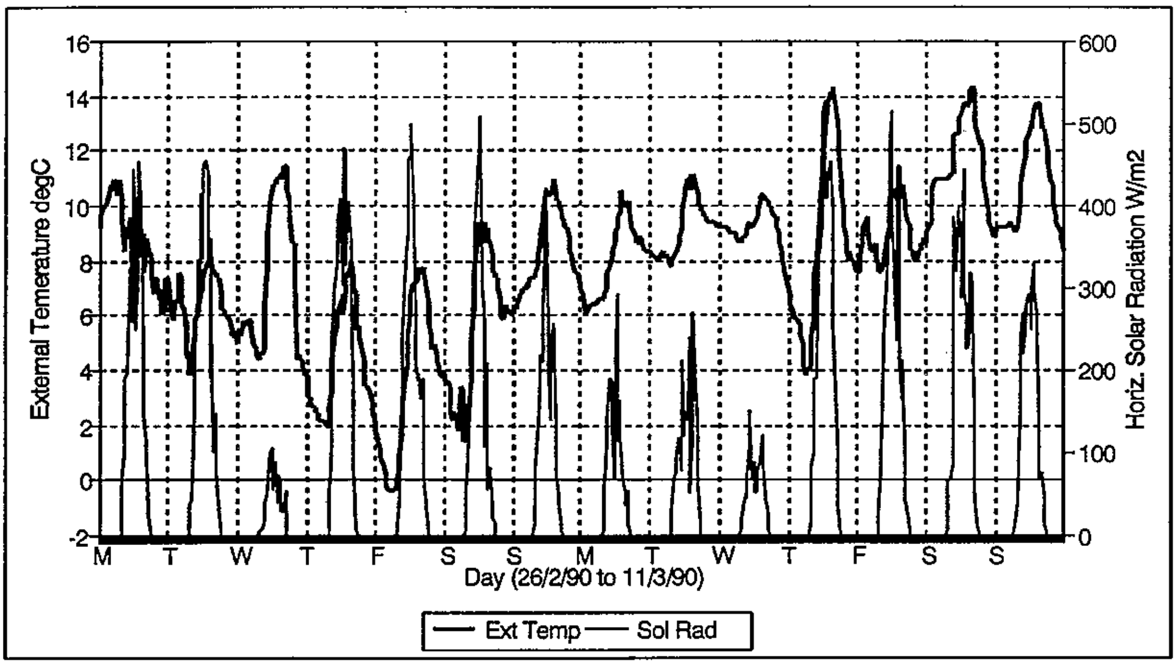
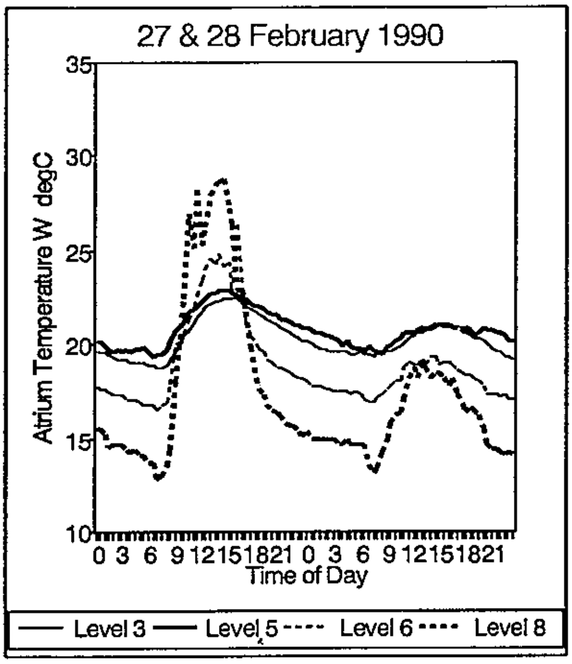


FIG 6 External Temperature and Solar Radiation

The temperatures recorded within the atrium are shown in Figures 7 and 8 for the west and the east end of the atrium respectively for two sample days, one sunny and one dull.

What is apparent from these figures is that there was a positive vertical temperature gradient at the west end of the atrium from about 9am to 3pm during the sunny day. This gradient was less well defined at the eastern end of the building, with all levels except the top exhibiting similar temperatures. It is also noticeable that the temperatures at the east end of the atrium were consistently lower than at the corresponding level at the west end of the atrium. It is worth speculating that the reason for this is the assymetry of the building, with the storey height glazing at the eastern side of the atrium depressing the temperatures at this end. For the bulk of the time (between 5 pm and 7 am and during the dull day) an inverted temperature gradient is apparent at both ends of the atrium.



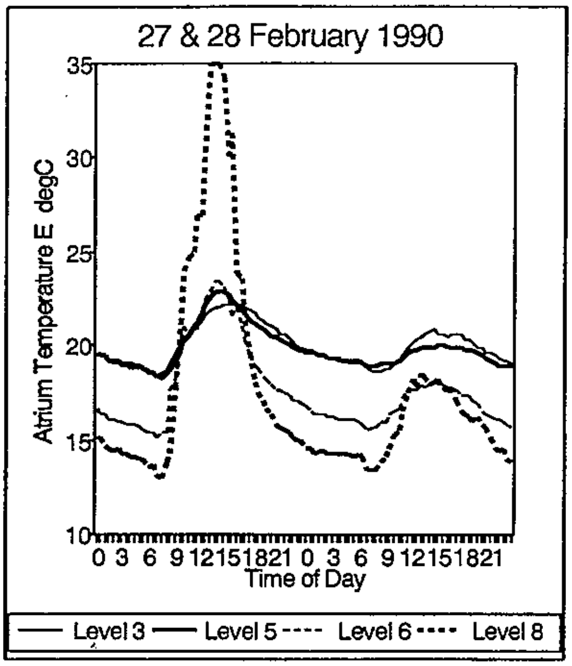


FIG 7 Atrium Temperatures-West FIG 8 Atrium Temperatures-East

Figure 9 below, shows the Carbon dioxide levels measured in the offices, atrium and externally for the period analysed.

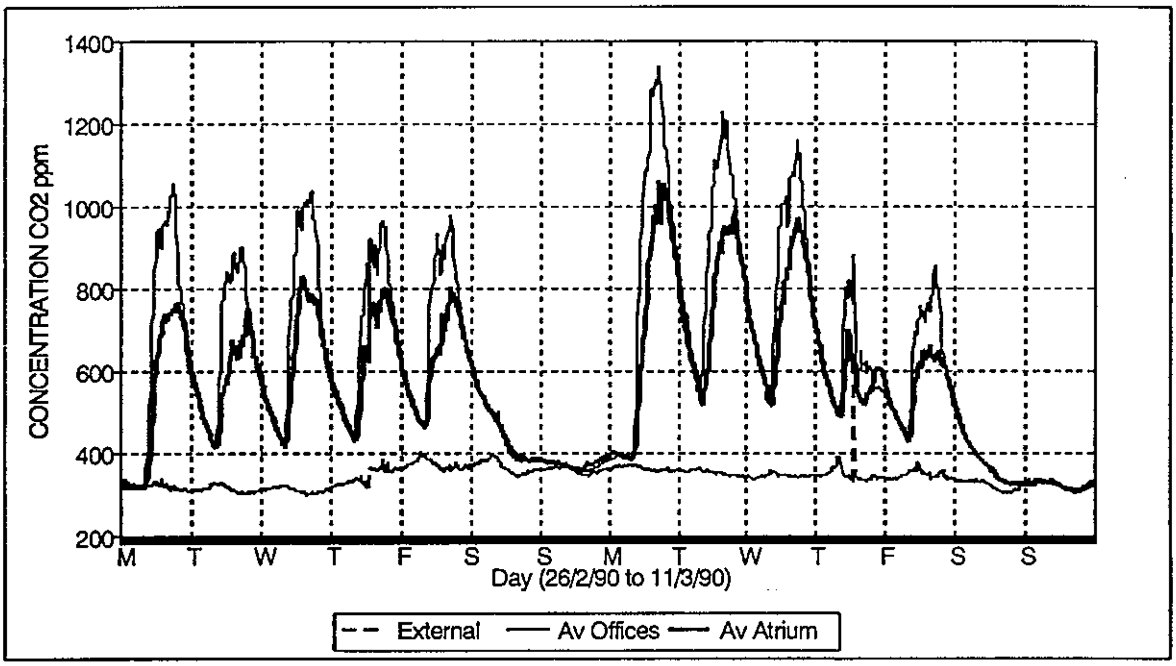


FIG 9 Carbon Dioxide Levels in Offices, Atrium and Externally

This figure indicates some fairly high carbon dioxide levels in the offices, especially at the start of the second week. Although the atrium CO_2 concentration did not reaching the level of the offices, it closely followed the profile suggesting a moderate air exchange between the two. It is interesting to note that there is no instance where the overnight CO_2 concentration fell to ambient during the working week.

A simple analysis was undertaken to obtain the whole building ventilation rate during the afternoon. The data showed that most afternoons, between 2 pm and 4 pm, the average carbon dioxide level in the building was fairly constant. It was assumed that 90% of the staff were working (468 people) and that they were each producing 21.6l/h carbon dioxide. The ventilation of the whole building is shown in table 1.

TABLE 1 Whole Building Ventilation Rate 2pm - 4pm

Date	Average building CO2 level above ambient ppm	Ventilation Rate ach
26/2/90	525	0.53
27/2/90	450	0.62
28/2/90	599	0.46
1/3/90	450	0.62
2/3/90	451	<0.62
5/3/90	730	<0.38
6/3/90	697	<0.40
7/3/90	626	<0.44
8/3/90	231	1.20
9/3/90	351	0.79

The ventilation rates shown with the "<" sign are for days where there was a consistent, though small, increase in CO2 concentration over the period, which would result in a lower than indicated ventilation rate. The high ventilation rates indicated for the last two days are most likely as a result of the opening of the atrium rooflights as these were particularly warm days.

TABLE 2 Overnight Ventilation Rates (8pm - 6am)

Date	Overall Ventilation Rate ach
26/2/90	0.12
27/2/90	0.12
28/2/90	0.12
01/3/90	0.15
02/3/90	0.12
05/3/90	0.11
06/3/90	0.10
07/3/90	0.13
08/3/90	0.10
09/3/90	0.13

Using the overall average carbon dioxide levels in the building it was possible to estimate the ventilation rate with a little more certainty during the unoccupied period overnight using the standard exponential decay equation. The results are shown in table 2.

This table shows that there was little variation in the ventilation rate over this two week period. The background leakage of this building is lower than that of the BRE low energy office, which at 0.2ach was believed to be reasonably airtight. These measurements also put the afternoon ventilation rates into perspective and suggest that external window opening was fairly common over this period.

Figure 10 Shows the decay in Carbon dioxide concentrations in all of the offices on level 5 and in the atrium for the night of 28 February.

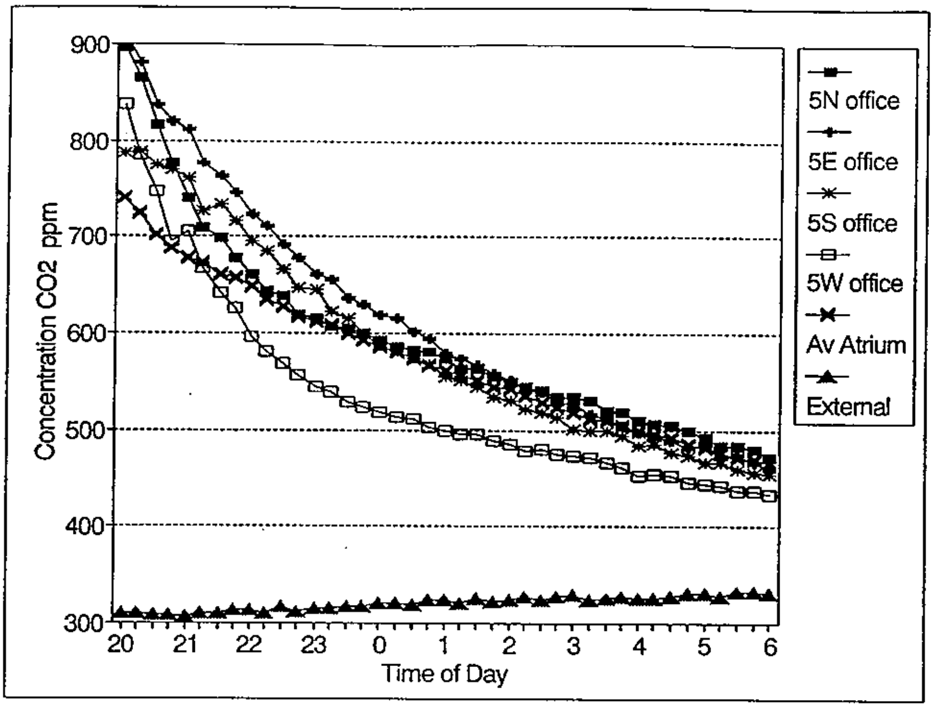


FIG 10 Overnight Carbon Dioxide Decay for 28 February 1990

What is interesting about this graph is that the decay of CO_2 in the west office is considerably faster than in the other offices and atrium. The concentration in this office is lower than the others after 9.30pm. This indicates that the ventilation rate in the west office is higher than the others and that there must be significant air movement into this office from outside.

An analysis was undertaken to determine these air movement into each of the level 5 offices from outside and from the atrium over this period. The results are shown in table 3 below.

TABLE 3 Overnight Air Movement in Level 5 Offices for 28 February 1990

Office	Average Vent Rate from Atrium m_3/hr	Average Vent Rate from Outside m_3/hr	Average Vent Rate from Outside ach
5 North	1499	65	0.05
5 East	149	206	0.13
5 South	105	160	0.13
5 West	1366	620	0.38
Total/Mean		1051	0.18

Although this analysis routine gives the flows into the office, it does not indicate the nature of the flow out. The mean ventilation rate for all the level 5 offices is somewhat higher than that computed for the whole building. The range of ventilation rates in the different offices is quite striking and the results for the west office confirm the interpretation of the decay curves. There was a moderate to fresh south west to westerly wind blowing overnight which helps explain the ventilation rate in the west office and also the low rate calculated in the north offices. The figures given for air movement from the atrium into the offices are less reliable because of the nature of the analysis but suggest a certain amount of through ventilation and a considerable air interchange between the west office and the atrium.

4.3 Summer Visualisation Tests

4.3.1 Method

The summer visualisation test were carried out on Saturday 14 July. About 10 people were working in the building during the morning.

The wind was from the east during the morning with the average wind speed at 10.00am being 3.5 m/s gusting to 5m/s. By 1.30pm the wind was from the south east and its speed had increased to an average of 4m/s gusting to 7m/s. the corresponding external temperatures were 19.4°C mid morning and 25.0°C at 1.30pm, the peak value was 26.2°C at 3.45pm. It was a bright, sunny, cloudless day. Overall, the weather conditions were nearly ideal, apart from the wind, for the summer visualisation tests.

As the building was to be tested in "summer mode" the rooflights, external windows and the louvres between the offices and atrium were to be open. All windows were checked and opened where necessary. Where private offices faced either the atrium or the external windows the entrance doors were left open except when locked (which also meant some external and louvre windows remained closed).

Exactly the same procedure was undertaken with the balloon tests as in the winter visualisation tests, though fewer balloons were released.

Smoke tests were more comprehensive than those conducted during the winter. They were carried out a similar manner to the winter tests. These tests concentrated on assessing the air flow both through the louvre windows between the offices and atrium, and to a lesser extent the flow through the external windows.

Measurements of air movement through the louvre windows were taken by holding a smouldering incense stick (for direction of flow) and the hot wire anemometer head adjacent to the centre of the window bay. Readings were averaged over a 5-10 second period. These measurements were taken at every louvre window bay (every 1.5m) As the external windows are top hung it was difficult to find a representative position for the hot wire anemometer head. The direction of air flow through the external windows was determined by the smoke and then the anemometer head was positioned in the stream and the flow averaged over 5 to 10 seconds.

4.3.2 Findings

The balloon tests indicated the following:

- vertical air movement at most points within the atrium.
- a considerable draught through the louvres of the level 4 offices on the south side of the building
- air movement just below roof level was very turbulent.

Rapid fluctations in air speed and direction made measurements impossible on level 4. Tests on levels 5, 6 and 7 were more successful as the flow through the louvres was less variable. Figure 10 shows the air flow direction and speed observed in the offices on level 5.

This figure shows that although the air movement through the north facade louvre windows was variable, through the other facades it was predominantly from the offices into the atrium with some fairly high air speeds being recorded. The measurements at the external windows were less reliable but not surprisingly showed high inward air speeds on the windward side of the building.

On level 6, it was found again that the overall air flow was predominantly from the offices to the atrium. The variation between facades was considerable and not consistent with the floor below.

On level 7, where it was detected, air flow was again into the atrium from the offices. In all but the south offices, the air flow was mainly into the offices from outside.

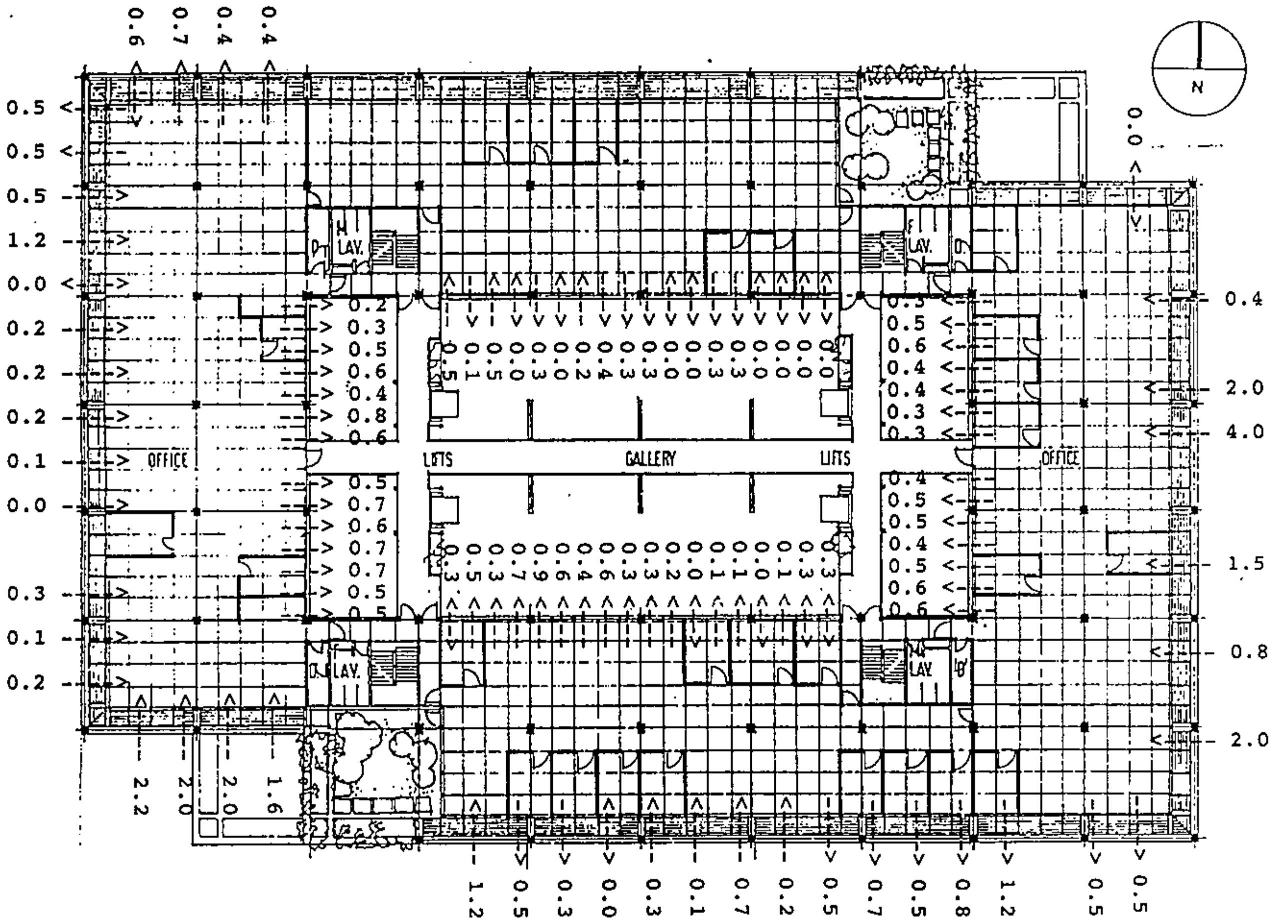


FIG 10 Horizontal Air Movement at Level 5

A summary of the air speeds measured between the offices and the atrium is shown in Table 4 below.

TABLE 4 **Summary of Air Movement Between Offices and Atrium for Levels 5, 6 and 7**

	North m/s	East m/s	South m/s	West m/s	Average m/s
Level 5	0.05	0.45	0.28	0.54	0.31
Level 6	0.27	0.21	0.04	0.09	0.16
Level 7	0.05	-	0.08	0.21	0.13
Average	0.12	0.33	0.13	0.28	0.20

This table confirms that the average flow from all of the offices, where measurements were taken, was from the offices into the atrium. There appears to be no particular consistency in the air speeds between different levels of the same elevation. This may be due to the wind speed and direction at the time of the tests. The overall average air speed does however reduce higher up the building. These measurements suggest that the major influence on ventilation in these offices is the stack effect. If the free area of the louvre windows is taken into account, the overall ventilation rate for the offices can be computed to be 4.6ach.

4.4 Summer Long Term Tests

4.4.1 Method

The equipment used for the summer long term tests was the same as that used during the winter long term tests. The only difference was that the office and atrium temperatures were recorded hourly. The equipment was installed in early July 1990 and recorded information until the end of August 1990.

As with the winter tests, it was not possible to record occupancy levels, external window opening or louvre window status. The status of the atrium rooflight was recorded, however, by the operators of the building management system.

For the analysis, it was decided to concentrate on 9 days of data from 21 July 1990 to 29 July 1990.

4.4.2 Findings

On the day of the visualisation tests it was decided to release carbon dioxide into all of the monitored offices in order to get additional information on ventilation rates while the building was unoccupied. This was undertaken with the external windows open or shut as they had been left from the previous working day, the louvre windows in their "normal" positions, and the rooflights open.

Table 5 below, shows the percentage of external and louvre window open and the measured ventilation rate from the decay of CO_2 in each office.

TABLE 5 Ventilation Rates and Window Opening

Office	Ventilation Rate Air Changes /Hour	% External Windows Open	% Louvres Open
7 North	5.0	30%	50%
6 North	2.5	30%	70%
5 North	5.8*	25%	75%
5 East	3.7	20%	70%
5 South	4.1	35%	80%
5 West	1.4	10%	70%
4 North	3.1	75%	80%

* this figure is unreliable as it is based on only two measured values.

It is not certain from these tests whether the air flow was from the offices to the atrium or to outside. On the basis of the smoke tests, (carried out as part of the visualisation tests) it is reasonable to suppose that the net flow was into atrium. Considering the small proportion of external windows open in some of the offices, some fairly high air change rates have been found. The lowest air change rate found (in the level 5 west offices) also corresponded to the lowest proportion of external windows open.

Further decay test were undertaken in the level 5 north office both with all the windows shut and all the window open. These revealed ventilation rates of 0.2ach and 7.3ach respectively. These figures are both comparable to those found in other tests carried out.

The weather during the nine days used for the long term analysis is shown in Figure 11 below. This figure indicates that all days had a considerable amount of sunshine except for the Friday and that some very high maximum temperatures were achieved.

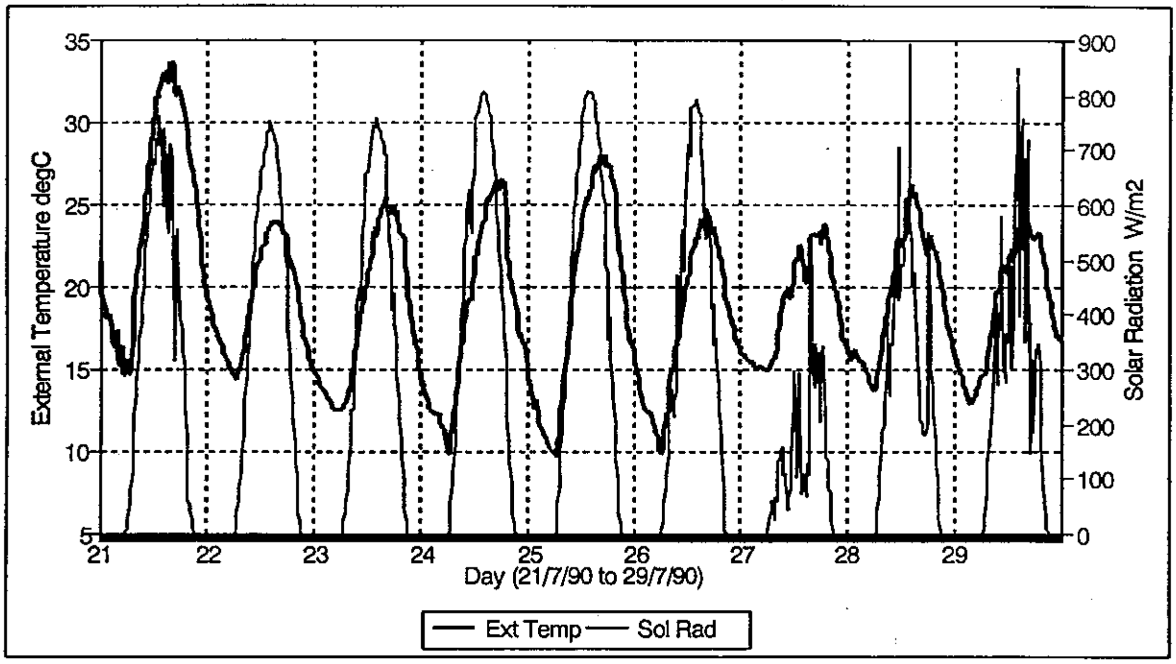


FIG 11 External Temperature and Solar Radiation

The average carbon dioxide levels above external, recorded in the offices and the atrium, are shown in figure 12. This figure indicates a relatively small increase in concentration of CO_2 in the offices during the working day and a correspondingly smaller increase in the atrium. The concentrations are back to ambient levels by early evening.

A detailed look at the data indicated that between 10am and 12pm, and between 2pm and 4pm, that the average carbon dioxide levels in the offices stayed fairly constant i.e. steady state conditions had been achieved. Table 6 below indicates the air change rates calculated for these periods for each day.

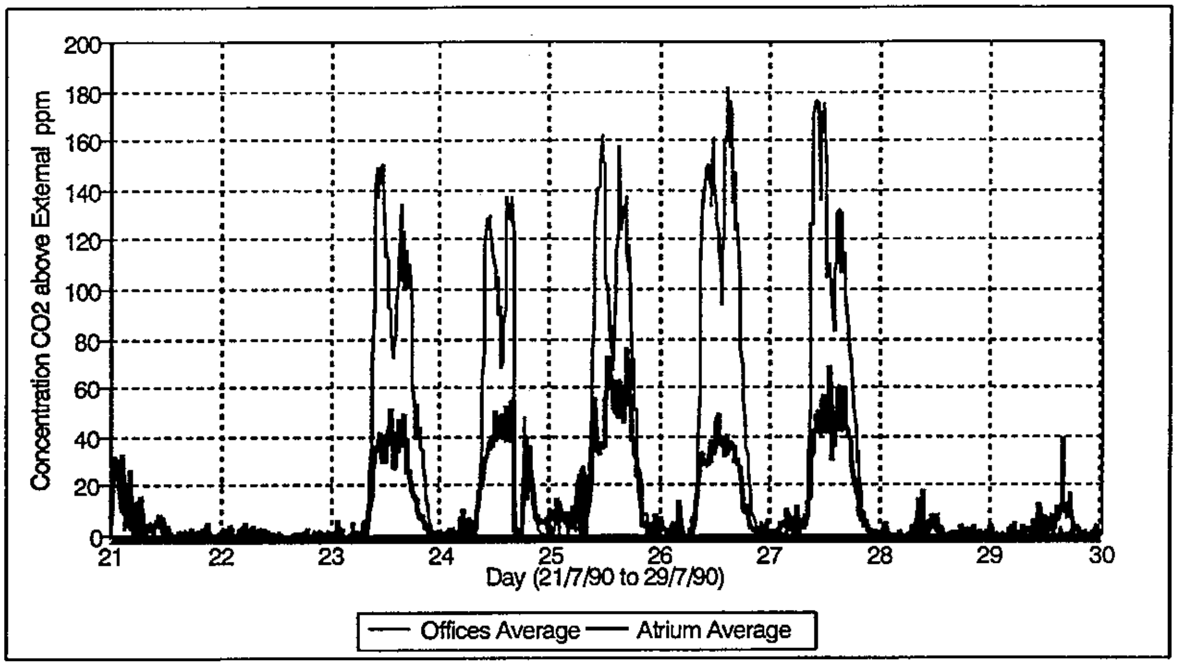


FIG 12 Average Carbon Dioxide Level in Offices and Atrium

TABLE 6 Average Office Ventilation Rates

Date	Office Ventilation Rate ach 10am - 12 pm	 2pm - 4pm
23.7.90	2.0	3.9
24.7.90	3.5	3.7
25.7.90	2.9	3.3
26.7.90	2.8	2.6
27.7.90	2.5	3.6

This table indicates ventilation rates of a similar order to those found from the carbon dioxide decay tests. The higher levels recorded during the afternoon are probably due to greater window opening as the offices become warmer.

The atrium and external temperatures for 25 July 1990 are given in figure 13 below.

The temperatures shown are averages of the readings from four recorders for levels 3, 5 and 6/7 and two recorders for level 8 (the catwalk). The figure shows a positive temperature gradient from the bottom to the top of the atrium between 9 am and 9 pm. This indicates that there were good conditions for stack ventilation to occur. Throughout this period the temperature at the top of the atrium was about 8degC higher than the external temperature. Similar temperatures were recorded for most of the long term monitoring period.

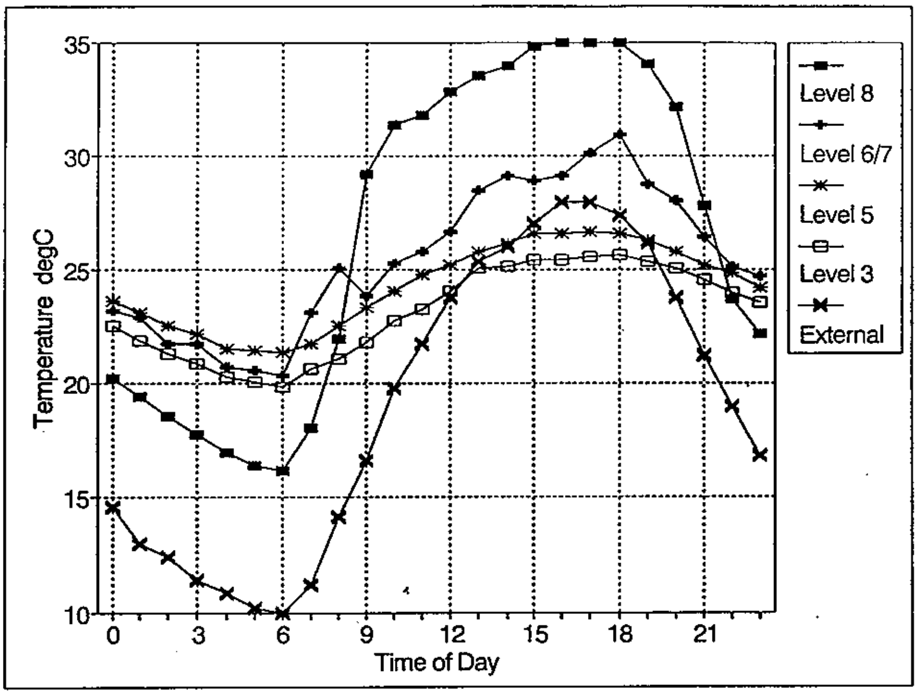


FIG 13 Atrium and External Temperatures for 25/7/90

4.5 Amenity

In the offices from levels four to seven, there are approximately 490 people working in 6700m2 floor space, giving an average of $13.5m^2$ floor space per person. According to the CIBSE guide figure A1.8, the minimum fresh air change rate required for this density of occupation where smoking is allowed (as in all offices in this building) is 0.3 ach. As shown in the previous section, this is no particular problem during the summer, but during the winter the computed daytime ventilation rates were close to this figure for a number of days. If, as suspected, there is a large proportion of cross ventilation, then the majority of incoming air to some offices will be contaminated air from the atrium and these fresh air requirements will not be met.

Figure 14 shows the carbon dioxide concentration in most of the monitored offices for Monday 5 March. This figure indicates that the concentration of CO_2 in all of the offices monitored exceeded 1000ppm by 2pm. The level five east office exhibited the highest concentrations and this was found to exceed 1600ppm by 5pm. These higher concentrations in the level 5 east office may be due to the main direction of air flow being from the atrium, the restriction to air flow through the louvres, or both as discussed earlier. Although these carbon dioxide concentrations are well within the Health and Safety Executive's long term occupational exposure limit of 5000ppm, they exceed the recent ASHRAE standard 62-1989 which has set an upper concentration limit of 1000ppm for comfort criteria.

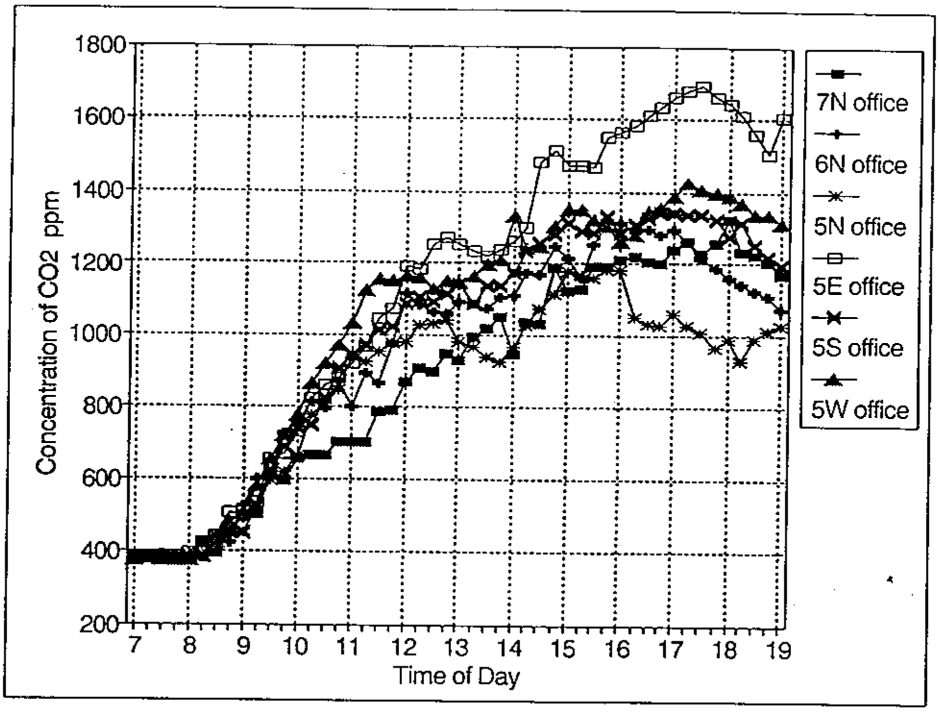


FIG 14 Office Carbon Dioxide Concentrations for 5/3/90

Although the day illustrated in the above figure had the highest CO_2 levels of the two weeks of data analysed, other days were observed with similarly high concentrations.

As the main design criterion of the atrium is to induce ventilation through the offices to reduce summertime temperatures, figure 15 below shows office temperatures.

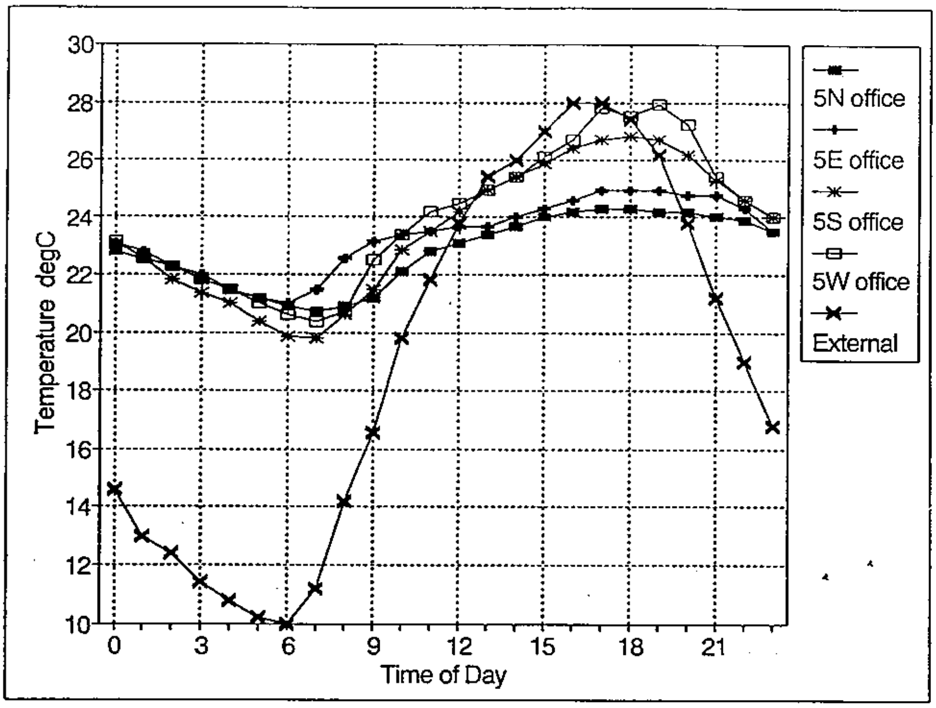


FIG 15 Office Temperatures for 25 July 1990

This figure shows that the peak office temperatures were less than the maximum external temperature. In the north and east facing offices, the maximum temperature was 3degC below the peak external temperature. Although figure 13 indicates that there was likely to be some stack effect induced cooling in the morning (before the external temperature exceeded that of the offices) the temperatures measured indicate that it is probably the high thermal mass of the structure which is moderating the internal climate given the high levels of casual gains from the occupants and lighting (about $30W/m^2$). Even during the afternoon, the induced ventilation will still help to make the offices feel more comfortable. The potential for overnight cooling is considerable, especially if the external windows are left open (as was observed for the visualisation tests) as well as the roof lights (standard practice for very warm weather).

5. CONCLUSIONS

5.1 Winter Strategy

It is clear from the winter visualisation tests that the air movement observed in the atrium was not as the design strategy on the day of the tests. It was found that the air movement in the atrium was generally from east to west at low level and from west to east at high level with downward flow at the eastern end and upward flow elsewhere. There was little air exchange between the offices and the atrium and this was often in the opposite direction to that shown in the design strategy.

It seems likely that the air movement is largely driven by the underfloor heating, as the design strategy intended, but that this is significantly influenced by the external glazing at the eastern end of the building. There is limited underfloor heating at the eastern end of the atrium due to the restaurant extending into the atrium at level 3. There are no offices at level 7 at the eastern half of the atrium, there is instead storey height single glazing to the outside. Both of these factors would confirm the observed down draught at this end of the atrium and the corresponding horizontal and upward movements observed.

It is a little more difficult to explain the air movement observed between the offices and atrium. In the design strategy air movement through the louvres from the offices to the atrium is shown to be induced by the flow caused by the underfloor heating, however there is no indication as to how this air leaves the atrium or is replaced within the offices. Presumably this relies on external window opening or leakage and roof light leakage. The visualisation tests showed air movement in both directions, although most locations indicated no air exchange at all. It is not clear whether this exchange observed was due to thermal or wind effects.

The longer term winter tests however, indicated that although there was a significant amount of air exchange between the offices and the atrium it would not have been possible to quantify it with the instruments used during the visualisation tests. The limited analysis undertaken suggested that the air movement was partially directional, tending to be from the windward to the leeward side of the building.

Although this analysis was undertaken for an overnight period, there were indications during the daytime that carbon dioxide levels in the offices on the leeward side of the building were considerable higher than those elsewhere. This may confirm that the main source of ventilation air to these offices is the already contaminated air of the atrium.

The levels of carbon dioxide observed in the offices were found to be moderately high on some days and although not approaching the current UK limit of 5000ppm they were well above the ASHRAE standard 62-1989 limit of 1000ppm for comfort criteria. These carbon dioxide concentrations suggest that there may be high levels of other pollutants within the offices, especially tobacco smoke.

The daytime ventilation rates calculated for all the offices were often little above the minimum fresh air requirement of 0.3 ach as given in the CIBSE guide Fig A1.8. The evidence is that in some offices this ventilation rate was lower, as suggested above. The analysis also revealed some fairly low overnight ventilation rates, lower than those of BRE low energy office which is considered to be reasonably airtight. Although this helps to reduce heat loss, the CO_2 level was discovered not to reach ambient levels before the start of the next working day. The overnight ventilation rates calculated imply that during the day external windows must be opened to achieve the minimum ventilation rate.

The main problem with the winter ventilation strategy is that it relies on the people sitting adjacent to the external windows and the louvre windows to open them for the benefit of all the occupants of the office. This does not appear to pose any difficulty with the louvre windows as around 70% are always open. The design of the external windows however, will lead to draughts at about desk level under certain conditions and may preclude their opening. Another problem regarding air movement is the preponderance of private offices, particularly facing into the atrium, which restrict through ventilation. In some offices over half the available louvre windows are in private offices.

5.2 Summer Strategy

The summer visualisation tests seemed to confirm that the air movement within the atrium and offices was as the design strategy. The ventilation rates measured however, were somewhat lower than predicted by the designers(3).

The balloon tests indicated that there was generally upward air movement within the atrium and that air was flowing into it from various offices.

The smoke tests indicated that the air movement between the offices and the atrium was generally into the atrium although fluctuations were observed in many locations, particularly on level 4. When this was quantified, it confirmed that the overall air movement from each facade on levels 5, 6 and 7 was from the offices into the atrium. This implies that the air movement was predominantly due to the stack effect. The overall ventilation rate derived from the air speeds measured was 4.6ach although there was a wide range between different offices. These tests indicated that there was no pattern to the ventilation rates found on each elevation. This was probably due to still significant effect of the wind.

The carbon dioxide levels observed during the working day for the period analysed rarely reached 150 ppm above ambient with the atrium maximum about one third of this value. These fairly low concentrations correspond to ventilation rates for the offices as a whole in the region of 2.5 to 4.0 ach. Although these ventilation rates will have some effect on cooling the offices, the high levels of internal gains due to the occupants, lighting and equipment suggests that a considerably higher rate would be needed for effective cooling. The office temperatures, which never exceeded the external temperature, and were 3degC below in the north facing offices on a sample day, imply that the high thermal mass of the structure had a considerable influence on moderating the internal climate. Overnight cooling of the structure appears to be the most important factor in keeping the daytime conditions comfortable. The number of desk fans observed in the offices, however, imply that many of the occupants find that conditions become uncomfortable on occasions.

As in the winter, the ventilation through the offices is largely controlled by the people sitting around the perimeter and restricted by the private offices.

Temperatures recorded in the atrium during the monitoring suggested that between 9am and 9pm there is a positive temperature gradient up the atrium and that the temperature at the top is some 8degC above external. These temperatures confirm that there are good conditions for stack ventilation to occur.

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DB03/Gateway/MT 5/2/91

COOLING SECTION

THE BIOCLIMATIC ROTUNDA IN EXPO'92 (SEVILLE)

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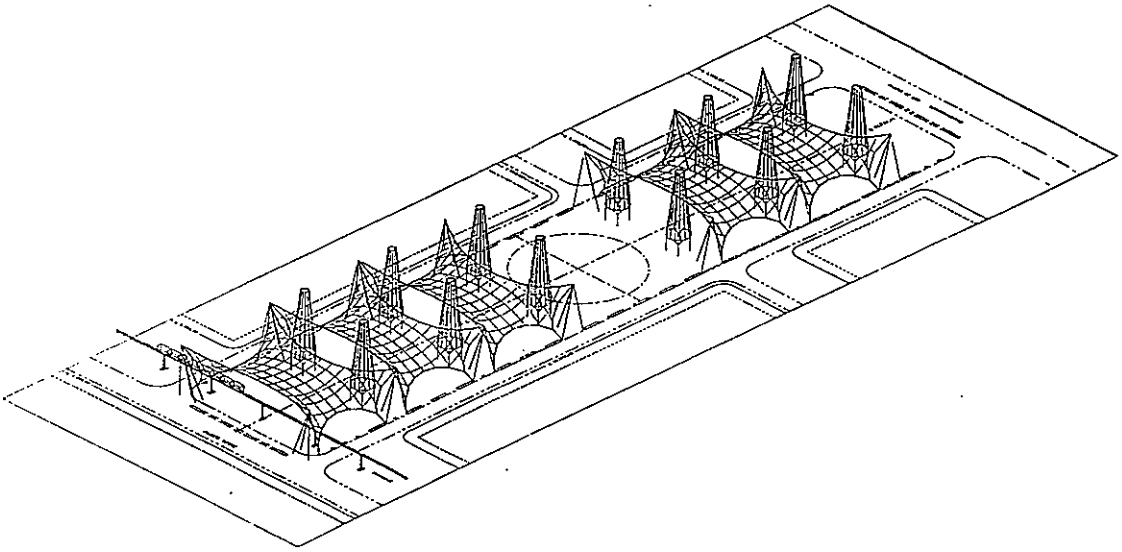


ABSTRACT

The Bioclimatic Rotunda forms part of the pilot plant set up as an experimental support for testing and evaluating different systems designed for the climatic treatment of outdoor spaces.

The entire project lies within a general framework of climatic conditioning of the outdoor spaces at EXPO'92, to which reference will be made throughout the paper.

We present the research work carried out in the bioclimatic rotunda and, in particular, the experimental, modelling and simulation activities.

We describe briefly the systems and natural cooling techniques employed and present a series of results obtained in the various stages of the work. In particular, we discuss the methodology followed for the evaluation of the levels of comfort resulting from the combination of different actions.

1 Introduction

From April 20th to October 12th 1992, Seville will be the host city of the EXPO'92 Universal Exhibition.

A significant percentage of the EXPO'92 site consists of outdoor spaces and the EXPO'92 organizers want these outdoor spaces to be the location of many social activities and not merely a physical connection between pavilions. Therefore, most of the waiting, resting, shopping and restaurant areas are located in outdoor spaces.

During the months of June to September, the climatic conditions in Seville are very harsh. Temperatures above 40^0 C combined with high values of solar radiation are not unusual.

Comparing what the EXPO'92 organizers want and what the climate of Seville permits, it is obvious that the outdoor spaces have to be conditioned in order to make the intended activities feasible. To this end, from mid-1987 EXPO'92 has undertaken multi- disciplinary research work aimed at developing an efficient and realistic methodology for the thermal conditioning of outdoor spaces within a series of aesthetic, economic and functional constraints.

The Bioclimatic Rotunda forms part of a full-scale pilot experiment set up to analyse the performance of different cooling techniques or strategies and to check the validity of several of the theoretical models developed.

2 Description of the Rotunda

2.1 Geometry

The bioclimatic rotunda has been designed taking into account the size, functionality and aesthetic appearance of the rest areas that will be distributed throughout the outdoor spaces at EXPO'92.

It has three levels linked by stairways and forms a square with sides of 31 metres. The two lower levels constitute the area intended to be used by occupants. They form two concentric circles with diameters of 24 and 16 metres respectively.

The difference in height between the various levels is 80 cm. and cascades fall from one level to another.

The rotunda is covered with a white PVC pyramidal covering (13% transmissivity) open at the top.

As previously mentioned, the purpose of the rotunda is to serve as a full-scale pilot experiment. As a consequence, it houses a considerable number of techniques and strategies aimed at the thermal conditioning of outdoor spaces.

2.2 Cooling strategies

The classification of the tecniques and strategies used will be done according to the different criteria for conditioning:

CRITERIA	ACTIONS
1 Control of solar radiation	- Covering (direct and diffuse) - Confinement (reflected)
2 Reduction of the temperature of the surrounding surfaces	- Cooling the covering by irrigation. - Cooling the pavement using running water underneath (fig 1) - Cascades (fig.1)
3 Lowering the temperature of the air	- Evaporative cooling (described below)

Evaporative cooling To provide cool air to the occupied space, the following natural cooling techniques have been used:

- Air handling unit (fig.2)

  Concept: (mechanical evaporative cooling)

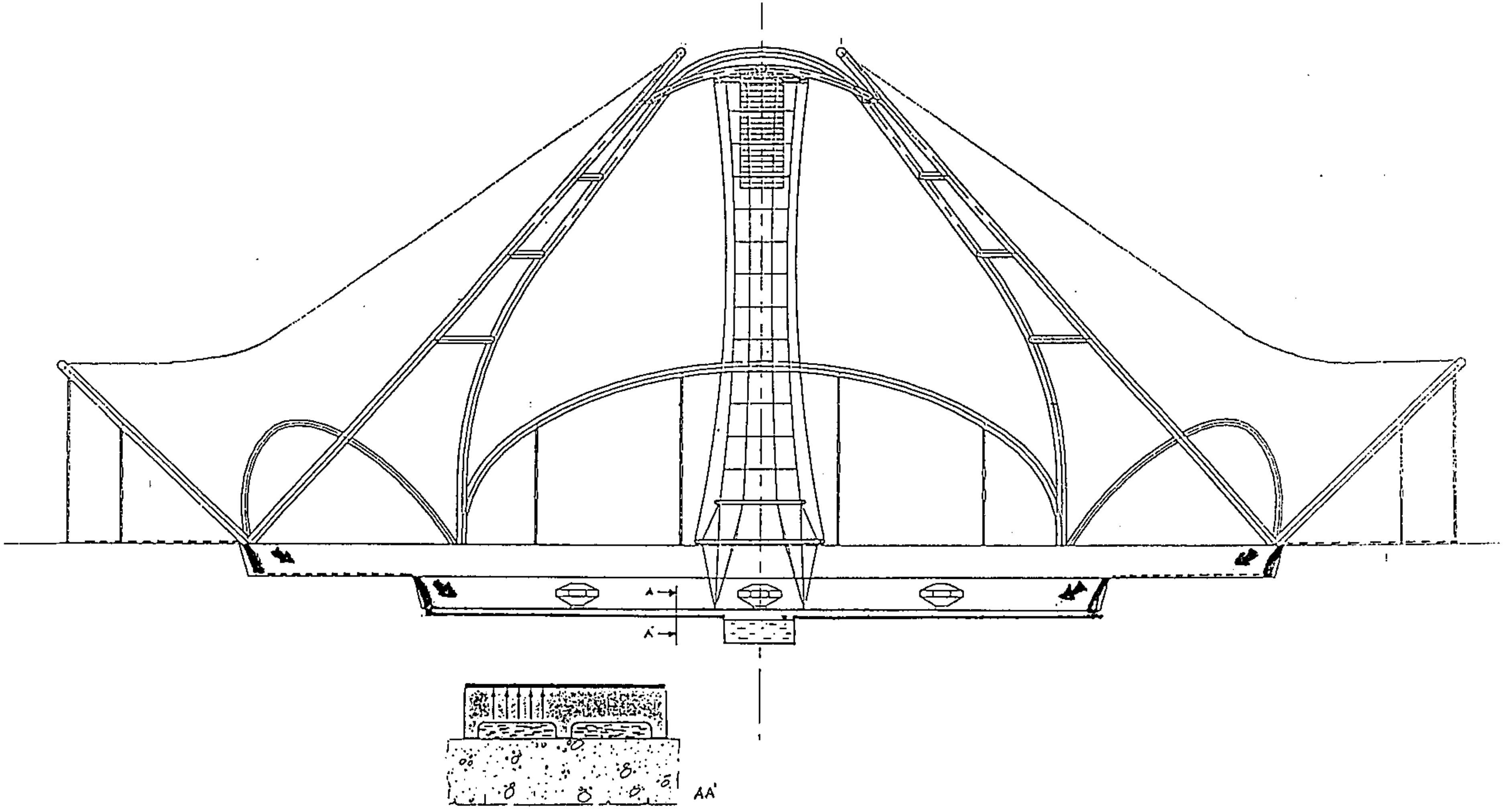


Figure 1: Cool Pavement and Cascades

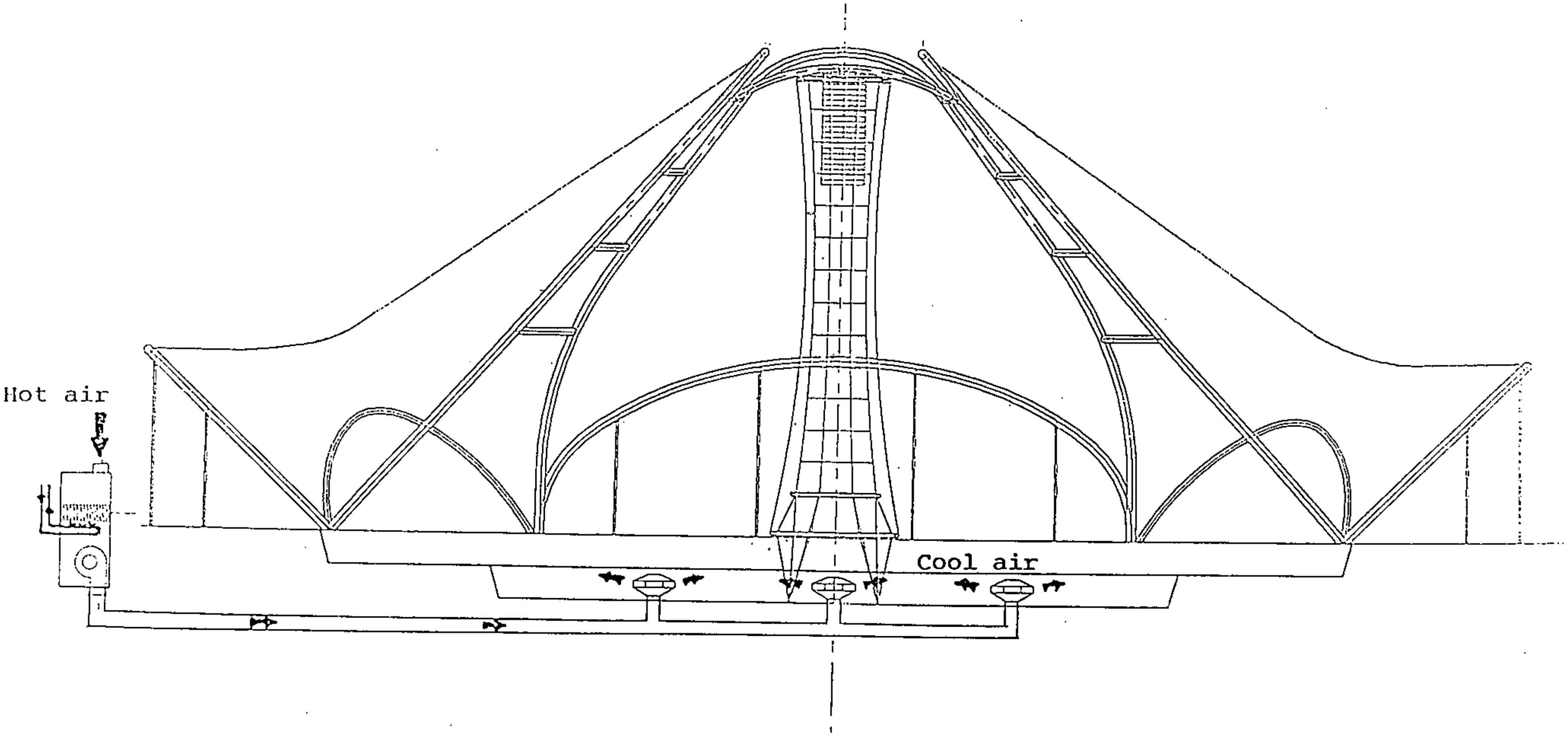


Figure 2: Air Handling Unit (AHU)

The air blown by a fan passes through a permanently humid packing fill. At certain times of the day, the air is post- cooled in the underground distribution duct.

In order to assure a suitable temperature in the massive material surrounding the duct, this is cooled during the night, taking advantage of the low temperature of the environmental air at this time.

- Micronizers in trees (fig.3)

  Concept: droplet evaporation (natural convection)

  Nozzles placed in the foliage of trees create an artificial fog by injecting water at high pressure through minute orifices. The small droplets (volume median diameter around 20 μ) evaporate in contact with the surrounding hot air which becomes cooler. As the cool air is heavier than the hot air, a continuous descending flow of cool air is obtained.

- Micronizers in tower (fig.4)

  Concept: droplet evaporation. Forced convection; driving force: fan.

  Nozzles in this case are distributed along the tower in different sections. The evaporation of the droplets cools the air blown by a fan placed at the top of the tower. The design variables and the control strategy have been carefully selected in order to maximize the cooling capacity while preventing people from getting wet because of non-evaporated water droplets.

- Micronizers in peripheral rings: wet barriers (fig.5)

  Concept: droplet evaporation. Forced convection; driving force: wind.

  In spite of the high degree of confinement existing in the rotunda, it is impossible to eliminate the entrance of air from outside in the event of wind.

  The only efficient means of preventing the wind from neutralizing the cooling of the air is to place a barrier which precools the air before it enters the occupied area. The barriers are based on the evaporative cooling of the air which crosses a row of micronizers.

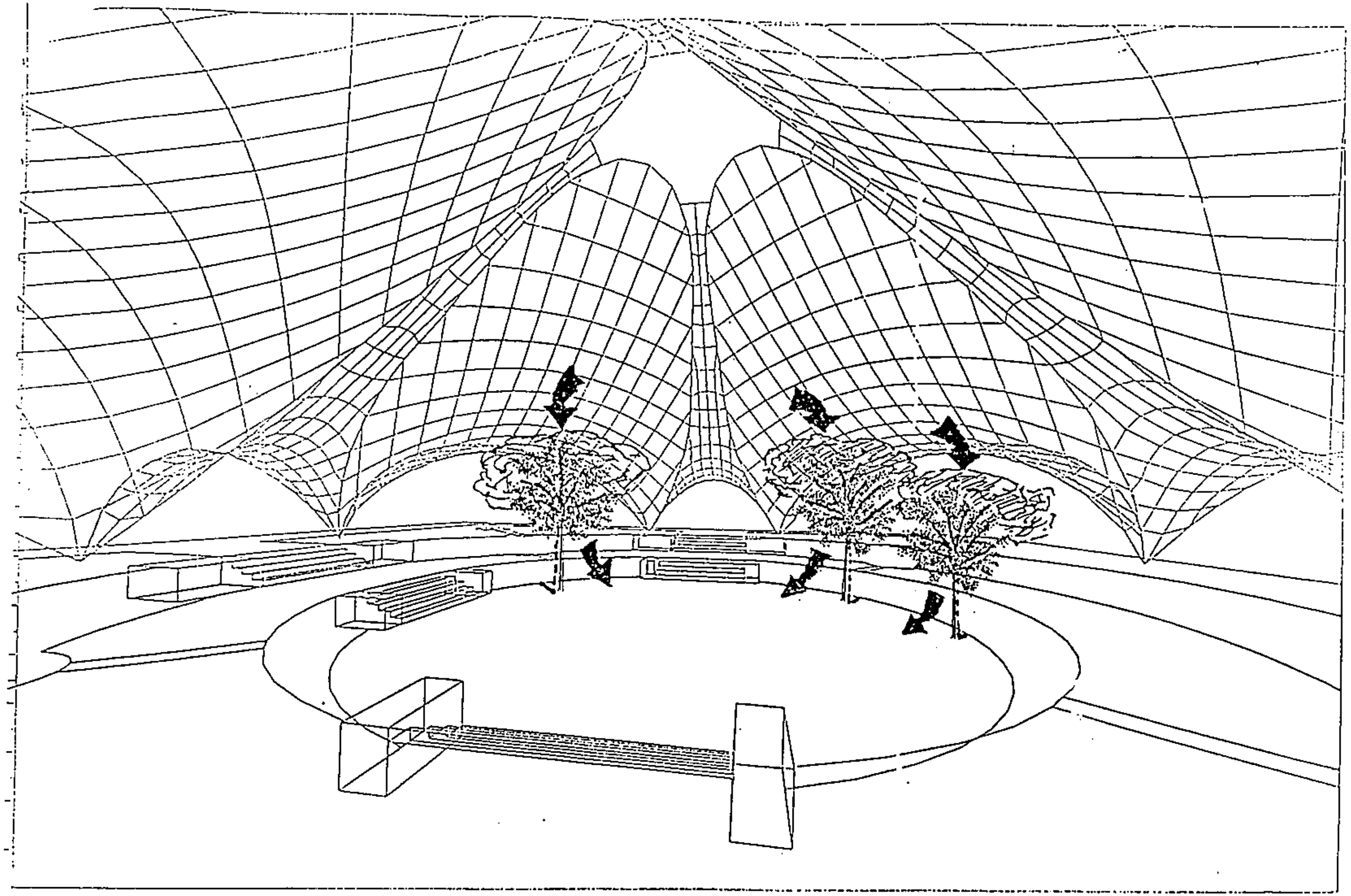


Figure 3: Micronizers in trees

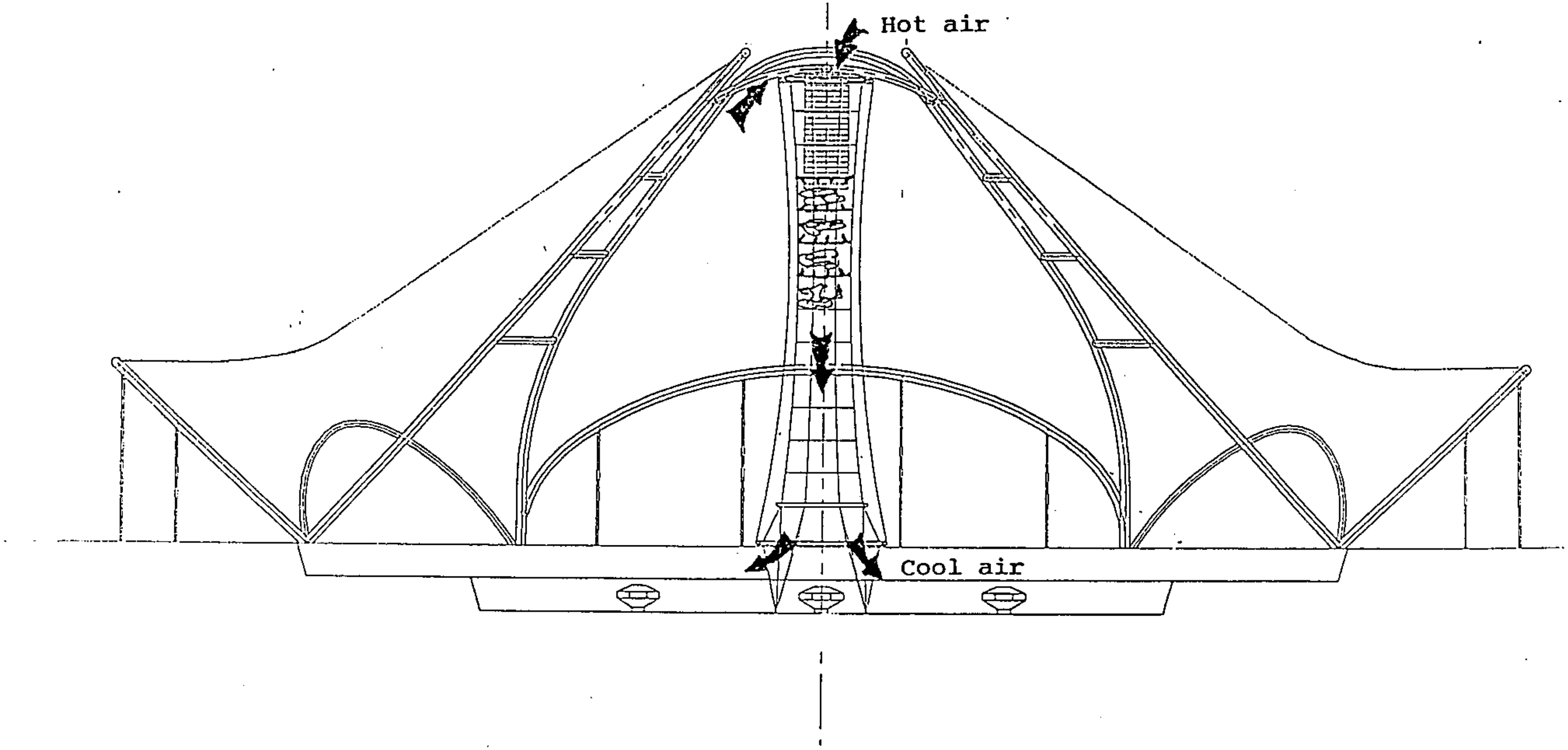


Figure 4: Cool Tower

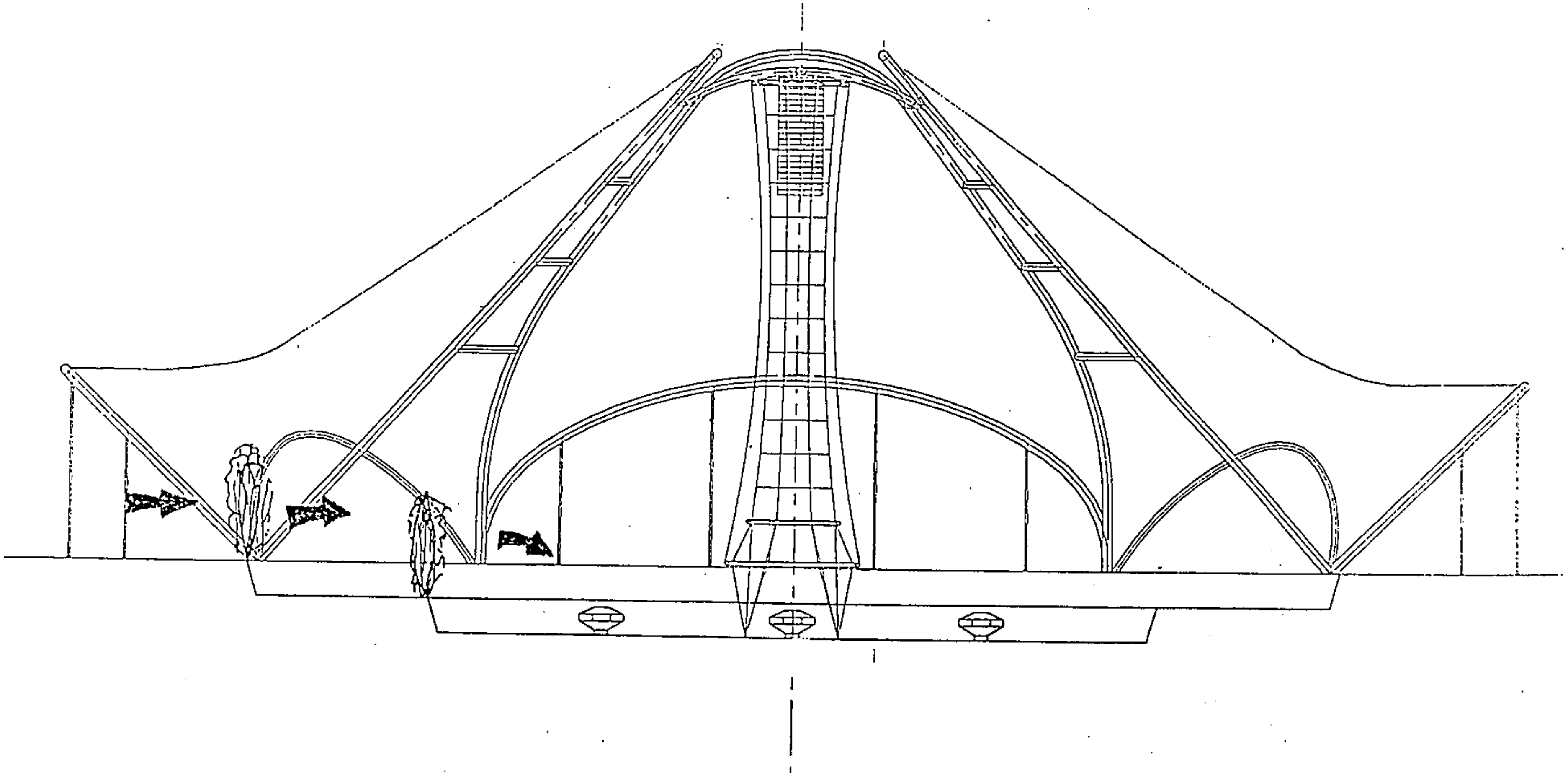


Figure 5: Peripheral Rings

3 Evaluation

3.1 Objectives and Methodology

The objective of the evaluation is three-fold:

- I to obtain data to describe the behaviour of each of the subsystems and in particular that of the natural air- cooling techniques.
- II to obtain data to describe the general behaviour of the rotunda.
- III to obtain data which may permit the validation of the various theoretical models.

The experiments took place in two phases:

- In the first phase (Summer 1989) emphasis was placed on the first of the objectives.
- In the second phase (Summer 1990) the aim was to evaluate the rotunda (objective 2), to which end:
  - a) The various subsystems were resized and their operational strategy redesigned in accordance with the results obtained in the Summer of 1989.
  - b) A control strategy was defined, based on an adaptative- predictive system which automatically decides which subsystem should be operated and at what intensity, as a function of the outdoor conditions and those existing within the rotunda.

Three different groupings of subsystems were evaluated:

Grouping I

Cooling of the covering by irrigation
Cooling of the air by micronizers in trees
Operation of the wet barrier when necessary

Grouping II

Cooling of the covering by irrigation
Cooling of the air by:

- AHU as basic element
- Micronizers in trees as support element

Operation of the wet barrier when necessary

Grouping III

Cooling of the covering by irrigation
Cooling of the air by:

- Micronizers in tower as basic element
- AHU as support element

Operation of the wet barrier when necessary

3.2 Experimental design

This includes a total of 41 sensors located in the rotunda plus the 5 in the weather station, with a sampling period of 1 minute and averaging and recording every 10 minutes.

The type and location of the sensors is in accordance with the objectives of the evaluation and gives rise to the following subdivision:

Variable measured	sensors	location of sensors
Water temperature	3	-central pond -representative input and output points of cool pavement
Pavement surface temperature	2	-representative points of the pavement
Covering surface temperature	2	-SW and NE facing planes of the covering
Air temperature	17	-input and output to AHU -input and output to underground duct -input and output to cooling tower -different points of the rotunda and adjacent spaces at different heights (0.5, 1, 1.5 and 2 m)
Relative humidity	17	-same as air temperature

In addition, air temperature, relative humidity, global solar radiation on a horizontal plane, wind velocity and direction are measured at the weather station.

3.3 Some experimental results

Figure 6 shows the covering temperature at SW facing plane (the least favourable) during August 16th (with irrigation) and 17th (without irrigation) and the outdoor air temperature. It can be observed a reduction of the surface covering temperature in the region of 16^{0}C due to the irrigation.

Figure 7a and figure 7b show respectively the air temperature and the relative humidity at different heights of the rotunda during August 14th, 1990, using grouping I. The control set-point was stablished to maintain 65% average relative humidity between heights 0.5 and 1 m.

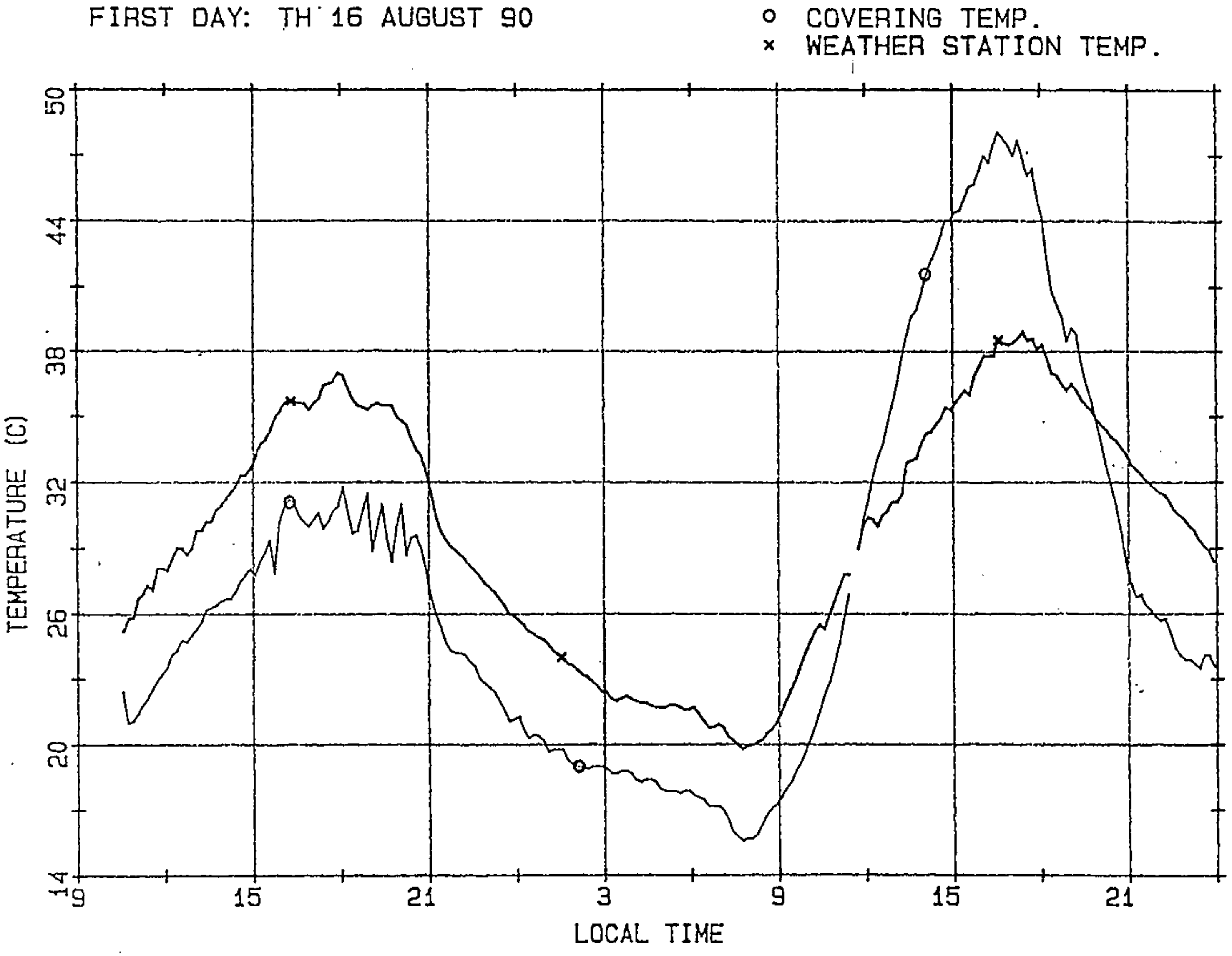

FIRST DAY: TH 16 AUGUST 90
o COVERING TEMP.
× WEATHER STATION TEMP.
TEMPERATURE (C)
50
44
38
32
26
20
14
9
15
21
3
9
15
21
LOCAL TIME

Figure 6

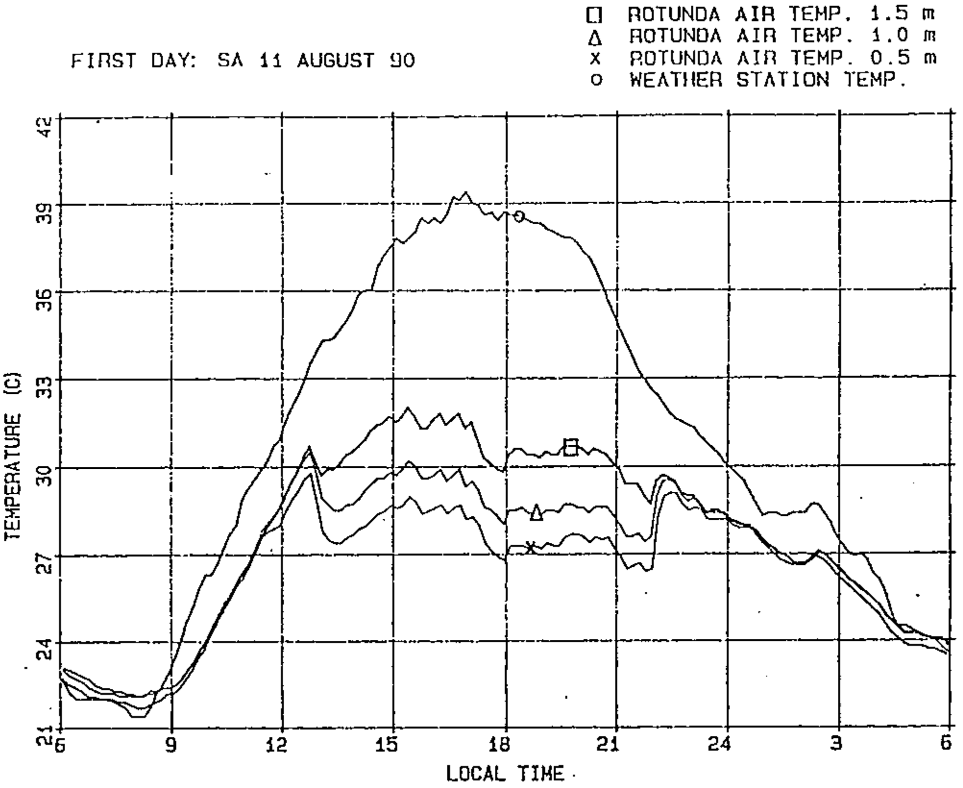


Figure 7a

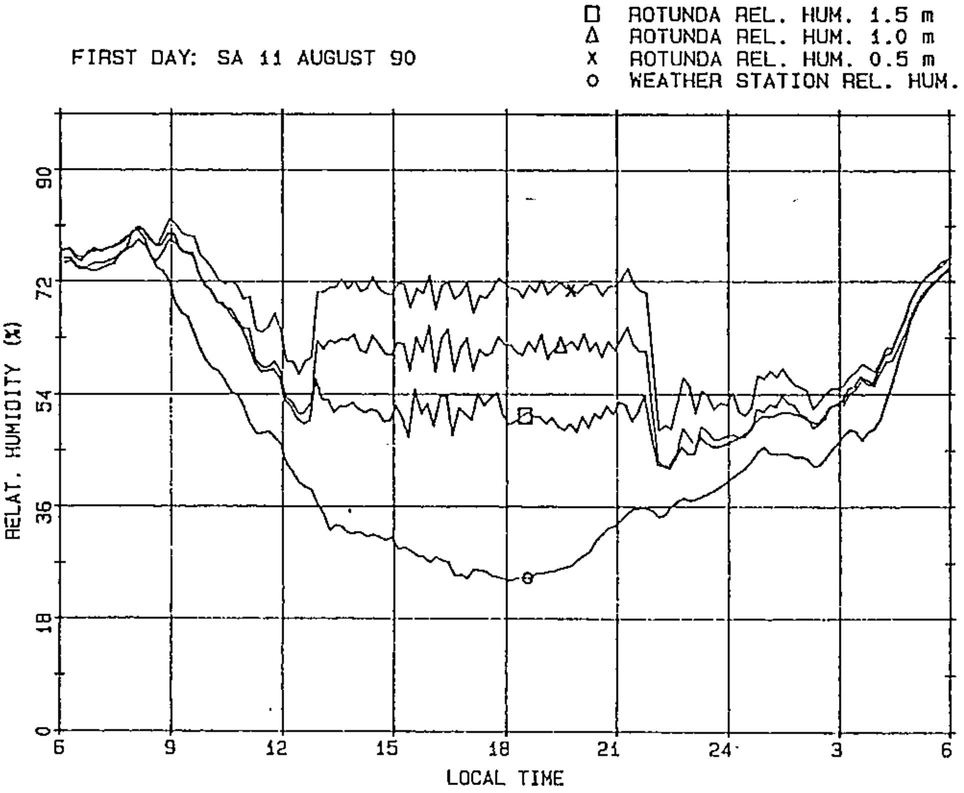


Figure 7b

3.4 Overall evaluation of the resultant climatic conditions

The overall results of the experiments should be evaluated in terms of the level of comfort achieved.

To obtain a given level of comfort in outdoor spaces, there are 5 variables with which we can operate:

Solar radiation
Temperature of the surrounding surfaces (covering, floor and vertical walls)
Air temperature
Air velocity
Relative humidity

Obviously, there are numerous combinations of values for these variables which lead to a given level of comfort. The number of variables to be manipulated and the intensity of this manipulation depends in each case upon many factors, of which the following may be emphasized:

* the characteristics of the area to be treated (geometry, dimensions, level of confinement).
* effectiveness and cost of the possible techniques to be used.
* the possibilities of integration of these techniques into the space without impairment of its aesthetic appearance.

Furthermore, the level of comfort required in each space depends on the activity to be carried out therein by its occupants (walk- way, rest area, restaurant, shopping centre) and the length of time they remain there.

Bearing in mind the foregoing aspects, the approach we have adopted for all the outdoor spaces, and in particular for the rotunda, is based on the analysis of what we call isocomfort graphs.

In each graph, and for a given level of comfort expressed in terms of grams/hour of sweat, we include the variables we wish to analyse. We thus obtain a series of curves which contain all the combinations of the selected variables which give rise to the required level of comfort.

In the case of the rotunda, we analyse simultaneously:

- temperature of the covering
- temperature of the air
- air velocity

The remaining variables are given a fixed value and do not appear because:

a) it is not possible to manipulate them because of a prior design decision.

b) the possible techniques for their modification would not be very effective.

The solar radiation falls into the first group, as this is controlled by a previously decided covering which has a transmissivity of 13 %.

The pavement temperature falls into the second group (the cool pavement scarcely affects the level of comfort if the air temperature is to be reduced). Likewise, the temperature of the vertical walls falls into this group (the cascades are very small and their radiant effect upon the occupants is thus insignificant).

The relative humidity appears implicitly in the graph since, given that we are only considering evaporative techniques for cooling the air, its value is predetermined.

Figure 8 shows the resulting isocomfort graph for 60 gr/h of sweat (MET=1) and outside design conditions (38°C, 30% relative humidity). This figure reveals, for example, that for zero air velocity the same sensation of comfort is obtained with:

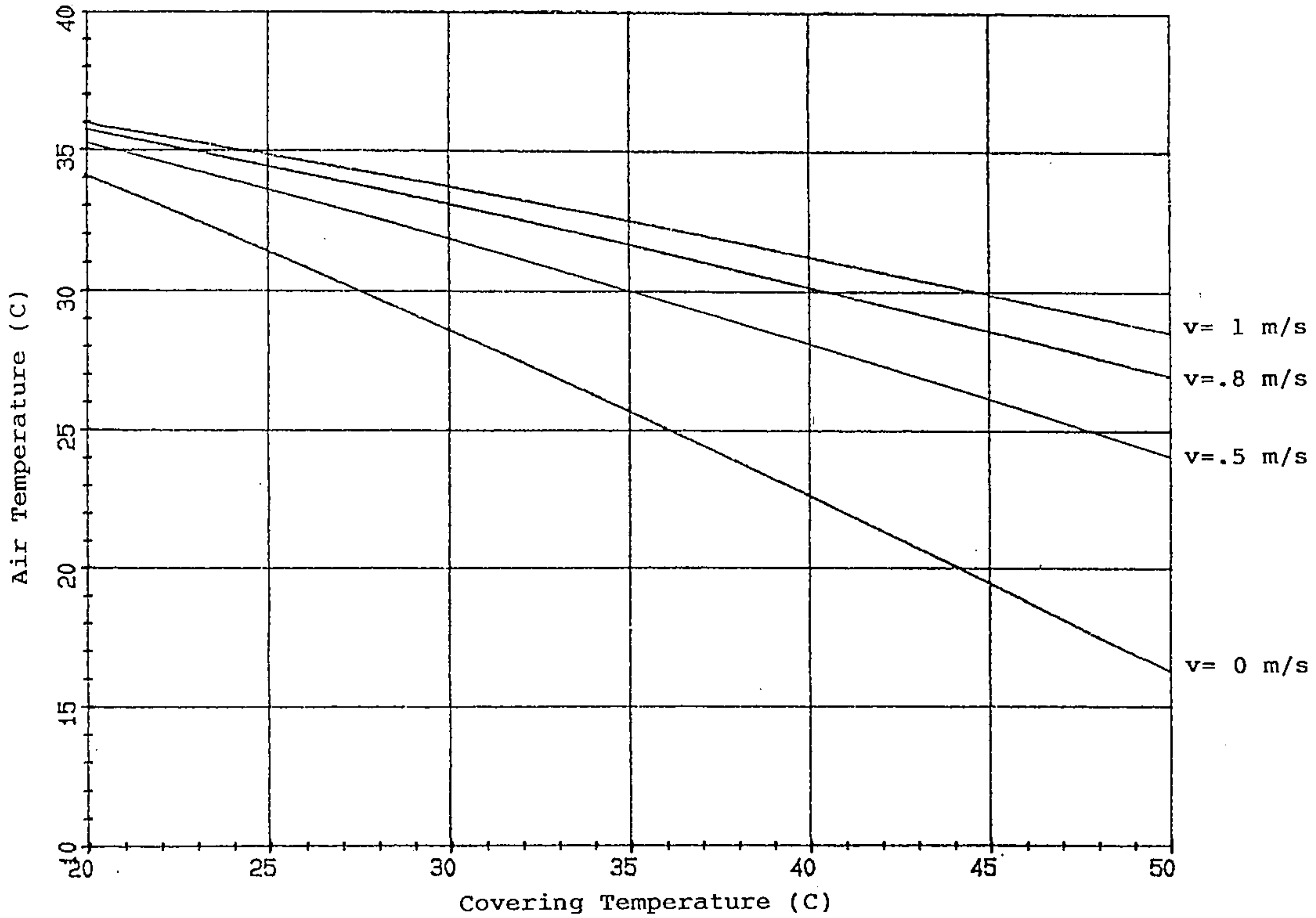


Figure 8: Isocomfort Graph (60 g/h)

Air temperature (°C)	Covering temperature (°C)
30	27
26	35
20	44

Similarly, for a given covering temperature (say, 34°C), the same sensation of comfort is obtained with:

Air temperature (°C)	Air velocity (m/s)
26	0
30	0,5
32,5	1

Given that the temperature of the covering without treatment reaches values in the region of 48°C (see Figure 6), irrigation of the covering is absolutely essential.

Figure 9 represents the experimental values for the air temperature and the covering temperature on August 11th, 12th and 16th 1990 from 12 to 20 local time with grouping 1, which does not provoke any appreciable movement of air. The comfort curves for 30 g/h, 60 g/h and 90 g/h of sweat (MET=1) are also shown.

Figure 10 represents the experimental values for the air temperature and the covering temperature on August 25th, 26th, 27th and 28th 1990 from 12 to 20 local time with grouping 2 which gives rise to a movement of air in the zone of approximately 0.5 m/sec. The comfort curves for 30 g/h, 60 g/h and 90 g/h of sweat (MET=1) are also shown.

On the days represented in figures 9 and 10 the outdoor ambient temperature ranged between 36 and 40°C.

It view of the fact that sweat rates below 90 g/h (Givoni; personal communication) do not produce any unpleasant sensation in occupants, it may be deduced that cooling techniques utilized give rise to sufficiently acceptable levels of comfort.

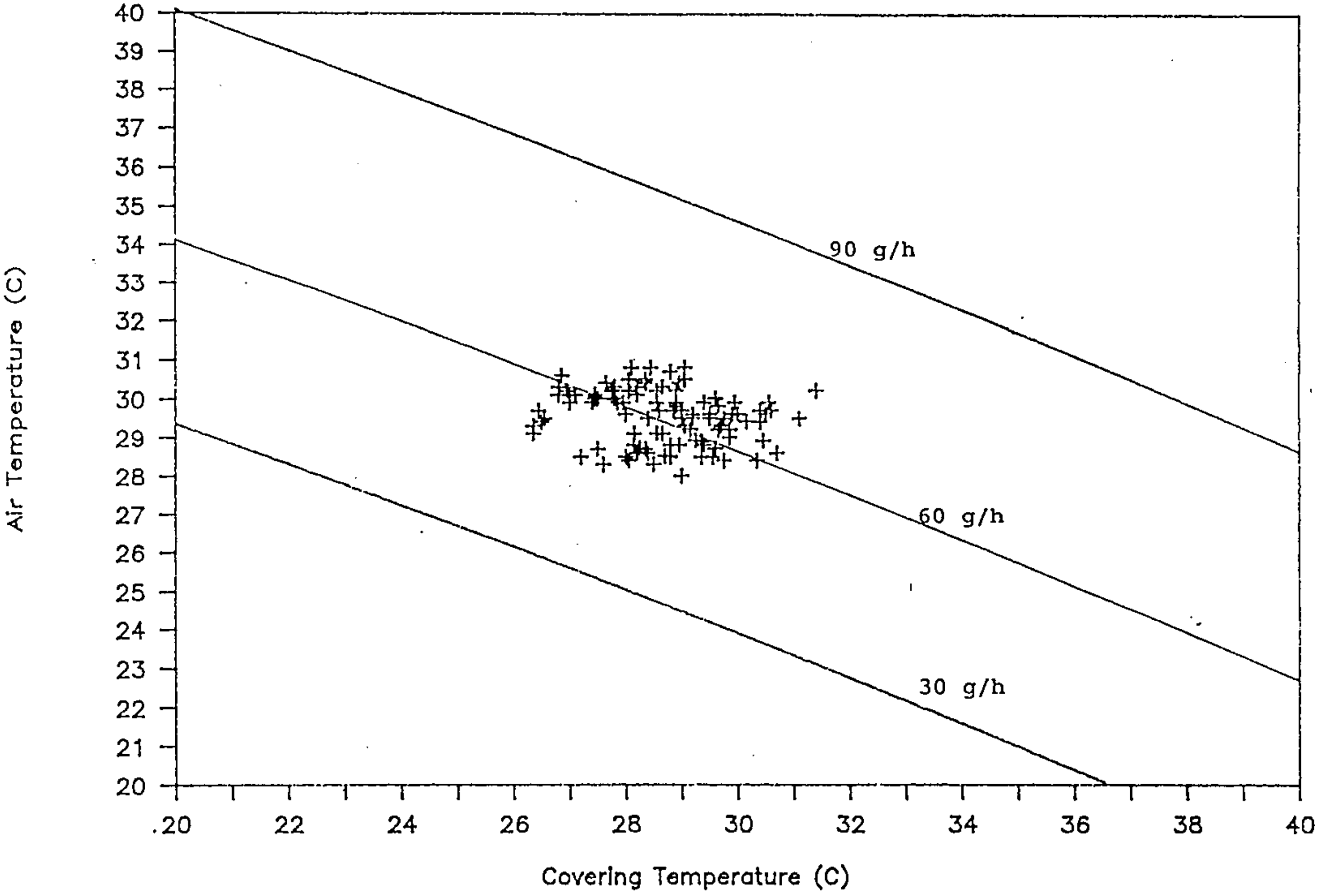


Figure 9: Experimental results (grouping 1)

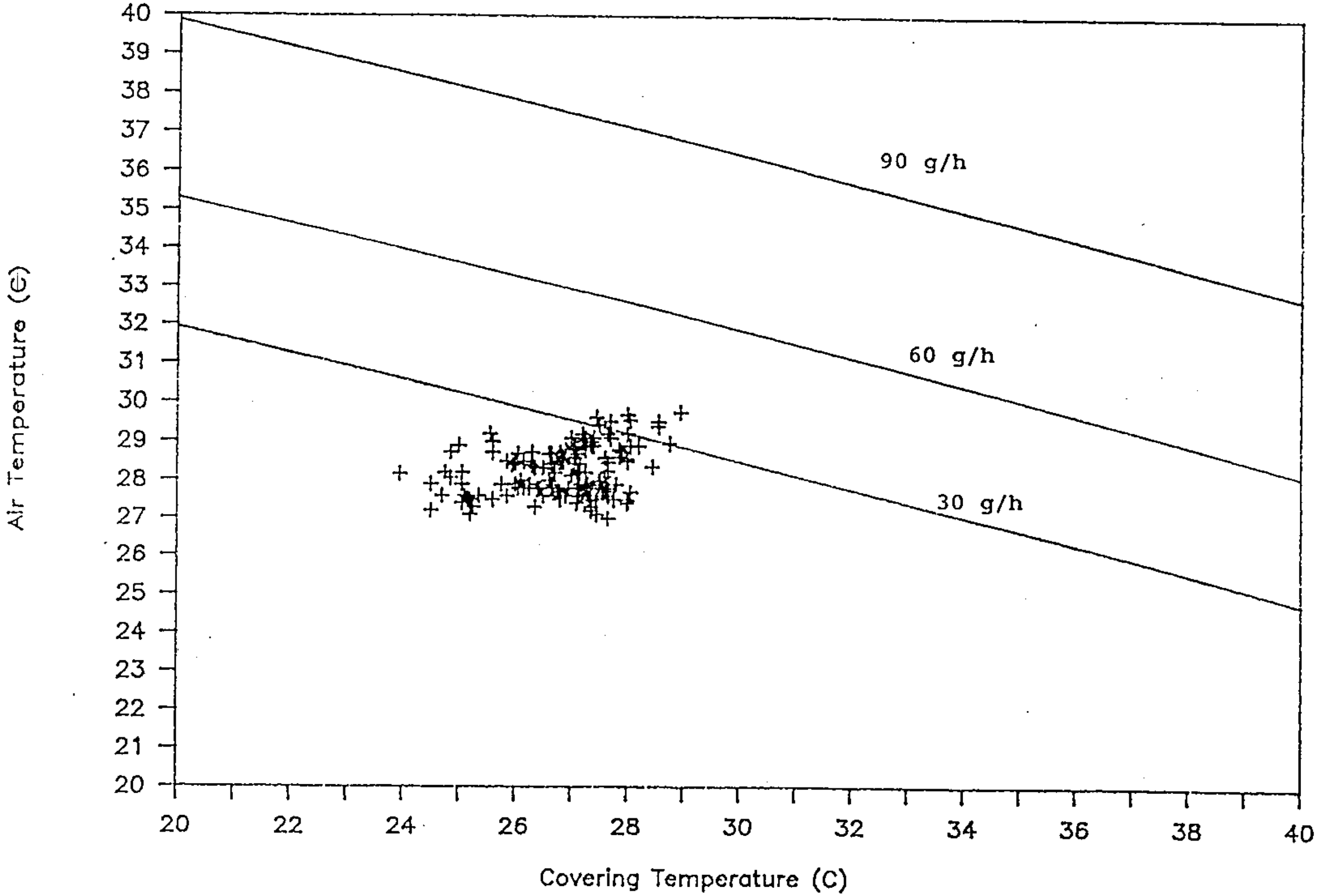


Figure 10: Experimental results (grouping 2)

4 Modelling and Simulation

4.1 Introduction and objetives

Experimentation alone is insufficient to evaluate the behaviour of a specific system and even more so if, as in the case of the rotunda, what is intended is the obtention of data for the design of future systems. Indeed, the analysis of an experiment tells us what is happening, but not:

> Why is it happening?
>
> Which subsystems worked correctly and which didn't?
>
> Why did this happen?
>
> Which design variables are relevant in each subsystem and which are secondary?
>
> How may the behaviour of each subsystem be improved and what is its point of optimum performance? etc.

In short, experimentation does not allow us to obtain a solid basis for systematically extrapolating the results nor for laying down the subsequent design guidelines. This basis may only be obtained via a process which includes:

MODELLING → VALIDATION ← EXPERIMENTS
↓
SIMULATION (Sensitivity analyses)

The foregoing process is particularly valid in the present case, in which the majority of the subsystems are new and for which there is, in consequence, no existing scientific literature.

Throughout the work of conditioning the outdoor spaces at EXPO'92 and in particular in the case of the rotunda, a fundamental objective has been the development of models based on physical principles (not on correlations) for each of the subsystems involved and the development of a computer structure capable of integrating the individual models and establishing the thermal and air-flow couplings between them.

4.2 Major models

Apart from the thermal comfort model, a sensitivity analysis of which was shown in Figure 8, theoretical models were constructed of all of the subsystems used in the rotunda. We will mention the following:

- cool pavement
- underground duct
- covering
- covering with controlled irrigation
- cooling tower
- wet barrier formed by micronizers
- air handling unit with latent cooling

In addition, models were constructed of other subsystems for potential use in spaces of similar characteristics, for example:

- other coverings
- covering with continuous water film
- wet barrier formed by water curtains
- air handling units with sensible and latent cooling sections
- ponds (shaded/not shaded; with or without water sprays or jets) used as a source of cool water for the air handling units, etc.

The computer programme responsible for taking the aforementioned models and expressing their links was the programme S3PAS, designed by the Cátedra de Termotecnia of the Seville University School of Engineering for CIEMAT-IER and expressly ceded for the present project.

The S3PAS programme not only serves as a support for the afore going models but also explicitly includes other subsystems such as conventional pavement or cascades.

In any event, the main purpose of S3PAS is to model the air-flow exchanges between the air in the conditioned area and the adjacent untreated space. In this way, a realistic and comprehensive modelling of the rotunda as a whole is obtained, which allows conclusions to be drawn for sizing the subsystems for other areas with different levels of confinement and of different size.

The whole modelling/validation/simulation process was carried out during 1989 and early 1990. The results obtained allowed us to resize the subsystems, substitute certain elements and design the control strategy.

4.3 Example: (cooling tower performance characterization)

As an example of the process described, we list below the research stages for the cooling tower:

- Modelling of the evaporation of a single water droplet in the air.
- Characterization of the droplet size distribution produced by the fog generators (micronizers).
- Modelling of the simultaneous heat and mass transfer phenomena occurring when air flow and fog (droplets of different sizes) come into contact in the tower.
- Design of the experiment (selection of the different variables).
- Experimentation (Summer 1989).

- Qualitative analysis of the results.
- Validation (Figure 11).
- Sensitivity analysis, in which the following items were examined:
    - Influence of the air flow rate (m^3/h).
    - Influence of the quality of the micronizers in terms of their VMD (Volume Median Diameter). Better quality implies lower VMD.
    - Influence of the water flow rate (l/m^3 of air).
    - Influence of the location of the micronizers within the tower.
    - Influence of the height of the tower (distance between the base and the micronizers).
    - Influence of outside conditions (ambient temperature and relative humidity).

  Figures 12 and 13 show, respectively, the outlet temperature and the percentage of evaporated water as a function of the tower height (distance in the figures) and the VMD of the micronizers.
- Specification of the control strategy to maximize the cooling capacity while avoiding people from getting wet because of non-evaporated water droplets.

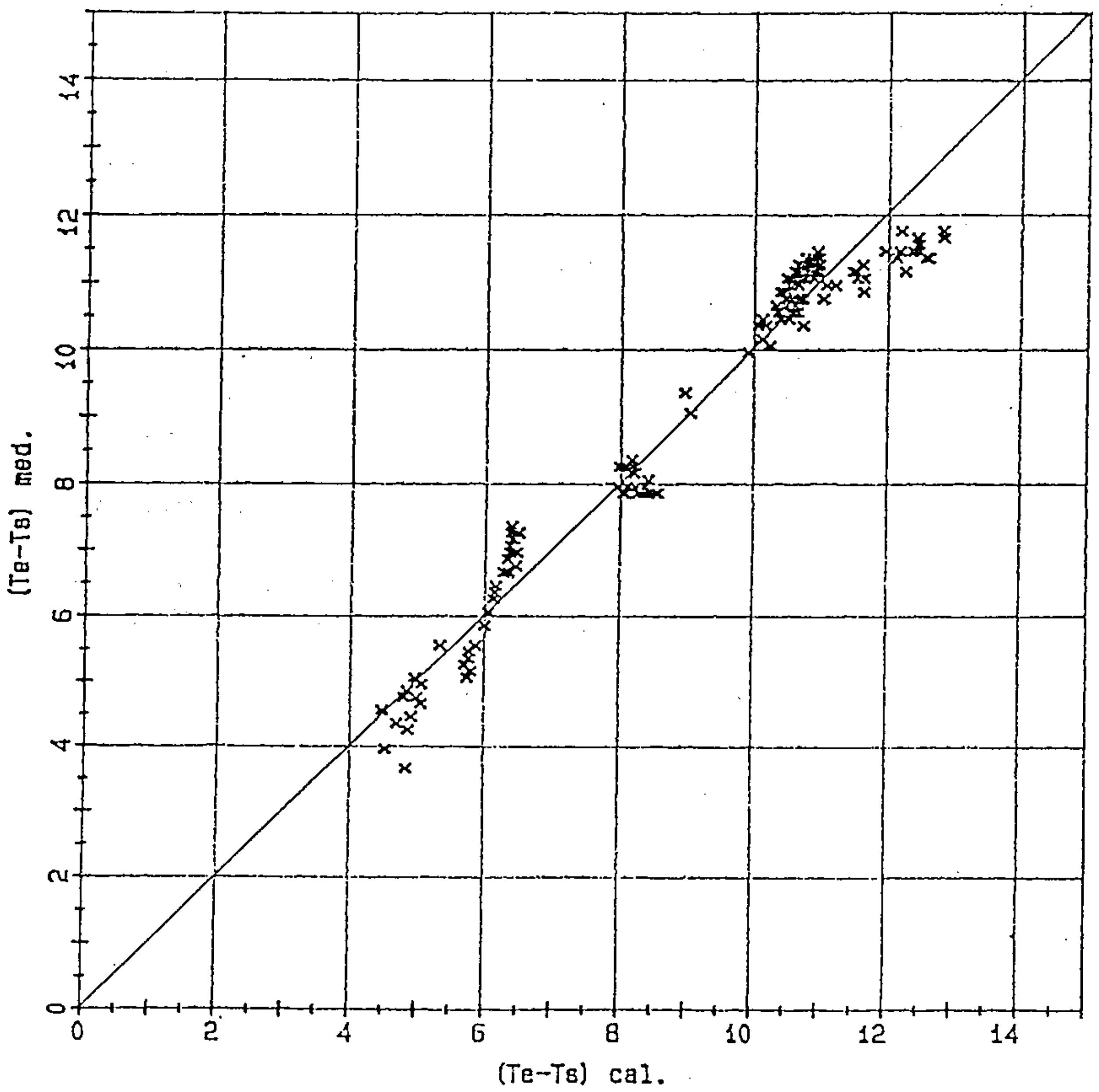


Figure 11: Comparison between measured (Y axis) and calculated (X axis) temperature drop (outlet minus inlet) in the cool tower

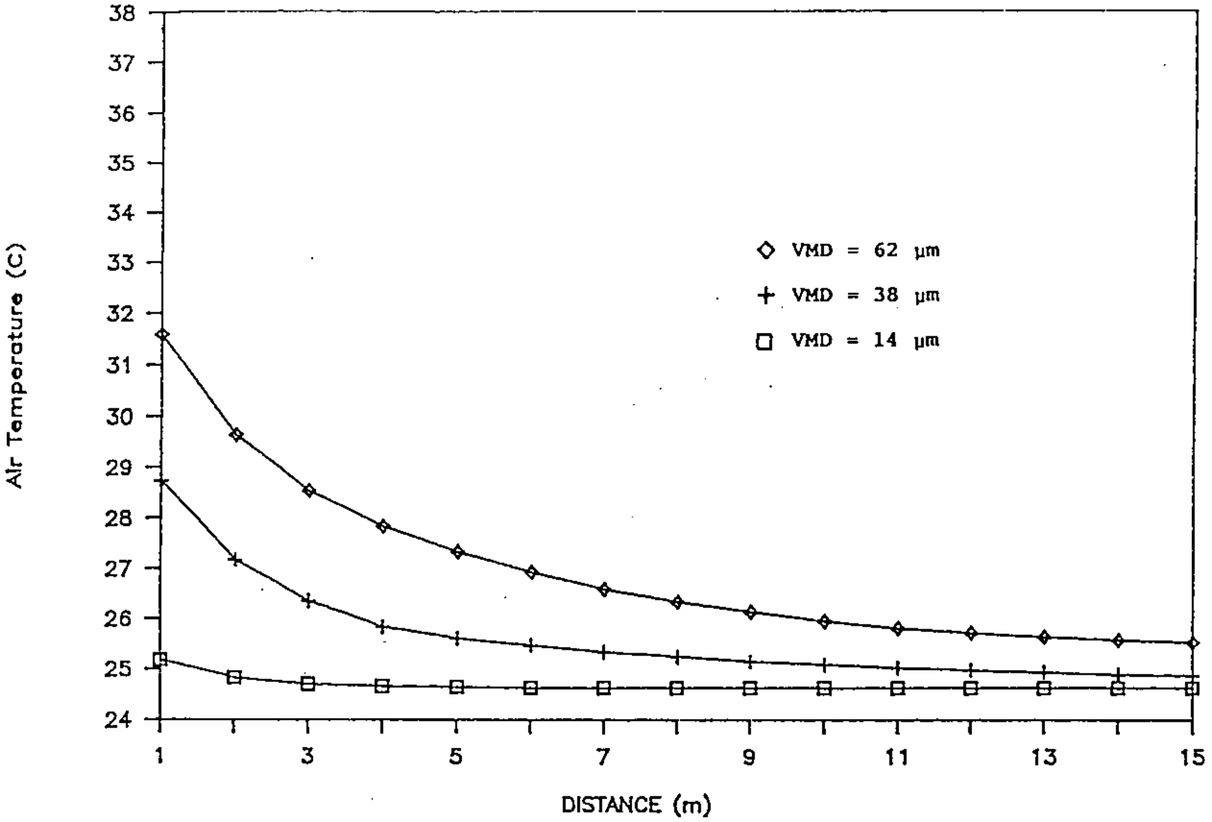


Figure 12

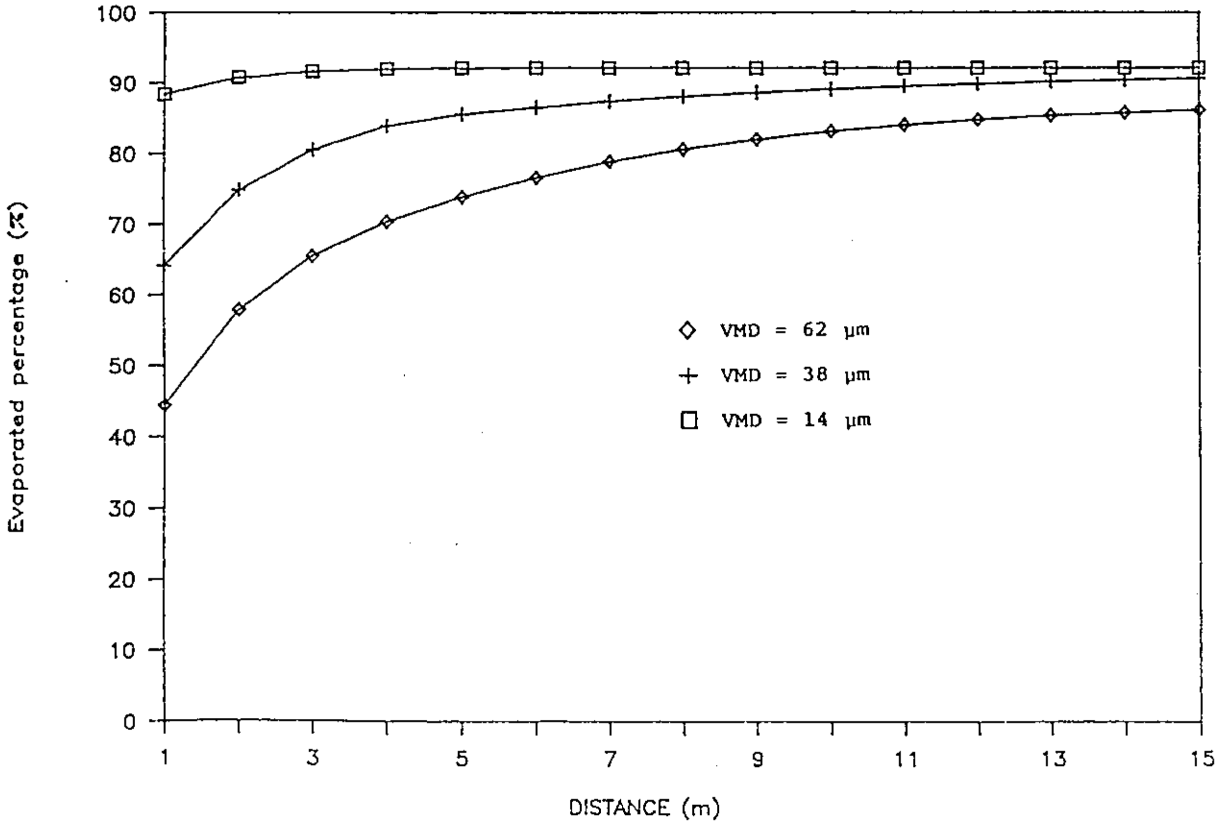


Figure 13

5 Conclusions

a) From a conceptual and methodological point of view, the work carried out has revealed:

  - Each of the subsystems analysed varies substantially in its behaviour depending on the selection of the design parameters which govern its operation.
  - The use of a given subsystem for conditioning outdoor spaces should be considered with the utmost care, since any apparently suitable concept can have a negligible effect if insufficient attention is paid to its design.
  - The real worth of each subsystem should always be evaluated in terms of the ultimate objective (the obtention of a given level of comfort) and in comparison with other alternative subsystems.
  - Modelling and simulation play a crucial role in the effective evaluation of subsystems and of complete systems. These two tools, together with monitoring and validation, allow us to obtain the necessary information for extrapolating the results to other applications.

b) From the point of view of the results, it has been shown that it is possible to condition an outdoor space at low cost using natural cooling techniques and that these techniques are not only compatible with the functional and aesthetic criteria applied to the design of the space but also of undeniable ecological value.

   It is important to point out here that the level of comfort for an outdoor space is less strict than in the case of an enclosed space (interior of building), among other reasons because of:

  - shorter staying time.
  - different functionality, which allows the use of low surface temperatures or movement of air (restricted in enclosed spaces).
  - psychological factors having to do with visual or acustic effects.

c) From the point of view of their applicability to the outdoor spaces at the EXPO'92, the present state of the studies allows us to assert that a large proportion of the techniques employed in the rotunda will be used in the mentioned open spaces. One exception is the cool pavement, which has been discarded due to its low level of efficiency in shaded areas compared to conventional pavements. Another exception are the underground ducts which will not be included due to problems of adaption to the major infrastructure work which it was necessary to carry out long before commencement of the installation of the climatic conditioning systems.

   The remaining subsystems will be used in improved versions and adapted to each application.

   It is worthwhile mentioning the presence of 12 cooling towers in one of the avenues. These towers are 30 m high and are topped with wind traps which will perform as fans in the rotunda tower.

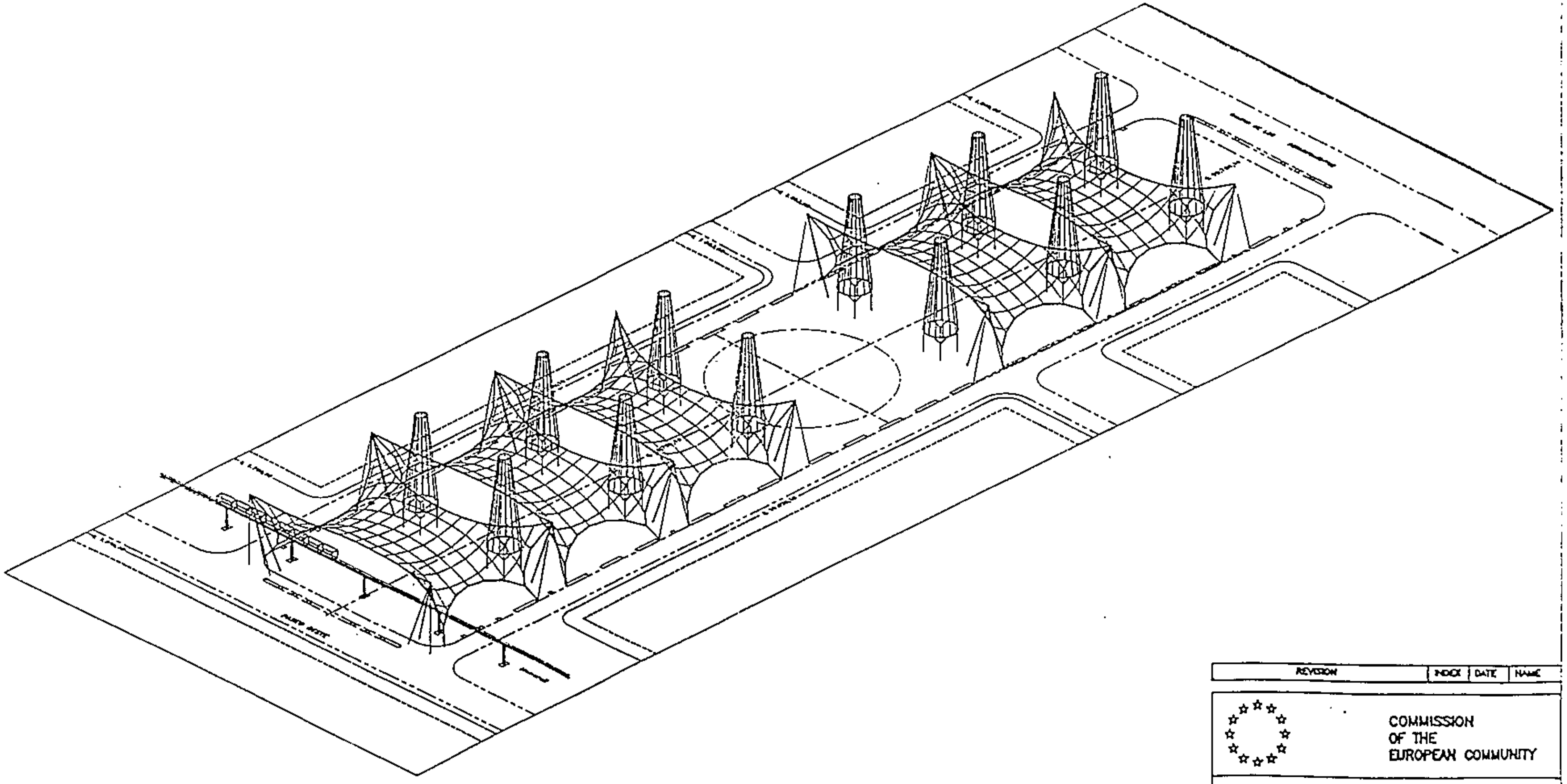
   Likewise, the case of the "palenque" (an area of 10000 m^2 where public festivities will be held) is of particular interest. It contains:

   - Irrigation of the covering.
   - 5 air handling units each with a sensible and a latent cooling section. The sensible section are supplied with cold water from the fountains within the palenque.
   - Wet barriers on the entire perimeter, consisting of a combination of water curtains and micronizers.

To make the climatic conditioning of the outdoor spaces at EXPO'92 possible it has not been sufficient, far from it, to have tested cooling techniques available. While this is an important factor, it should be acknowledged that the final materialization and integration has come about as a consequence of a series of factors, among which the following are the most important:

- The favourable attitude of the EXPO'92 design team and of the independent architectural teams that have participated in the project.
- The adoption of a highly interactive work plan which has meant that engineers and architects have been in permanent contact from the early stages of design.

All these factors mean that the result of the work represents the largest experience in the climatic conditioning of urban spaces ever undertaken in the world.



THE COOL TOWERS IN THE EUROPEAN AVENIDA

REVISION	INDEX	DATE	NAME

COMMISSION
OF THE
EUROPEAN COMMUNITY

SEVILLA
EUROPEAN AVENIDA
EXPO'92

DRAWING: UEBERSICHTSPLAN PRIMAERSEILNETZE	NO.	2821-810
	SCALE	1 : ---
	DATE	31.07.8?/??/DIE

JEAN-MARIE HENNIN - NICOLAS NORMIER

DR.ING. LIPPSMEIER + PARTNER

PARIS-FRANCE

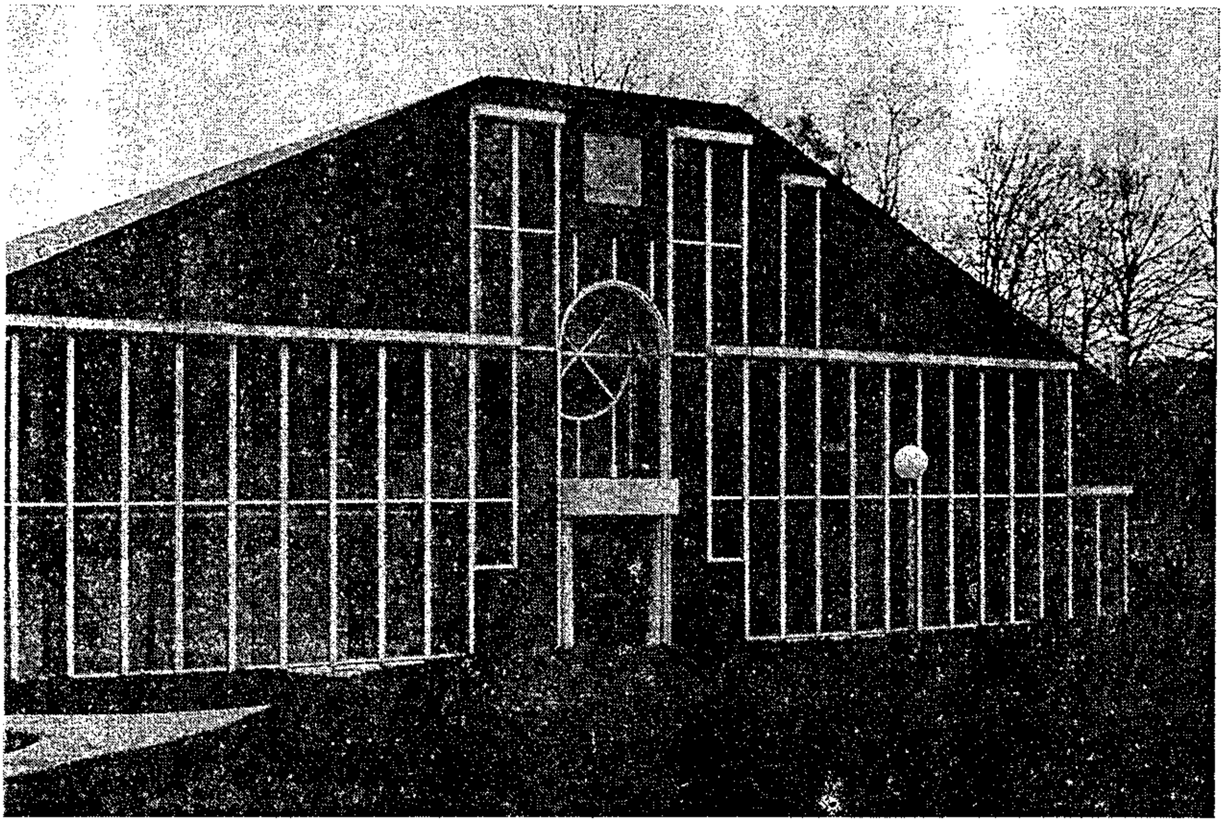
L+P

HEATING SECTION

Advanced Case Study

Auditoires FUL Arlon (Belgium)

Mass wall passive heating system



ABSTRACT

The FUL Research Institute in Arlon (south of Belgium) has decided to use passive solar heating techniques for its new building ("Auditoires"), occupied since October 1986. This two storeys building includes a direct gain heated central zone and two indirect gain side zones consisting of mass walls with integrated interior windows. The insulation level of the building is higher than belgian standards. The only glazed facade is south facing and includes roller blinds for night additional insulation. A gas fired heating system and several mechanical ventilation subsystems assist the passive solar features.The building has been selected as a candidate for the analysis of the mass wall passive solar heating system in the context of the "Heating Group" of the IEA task XI project.

INTRODUCTION

In 1985, the FUL Research Institute situated in Arlon, in the southern part of Belgium, decided to plan a new building in order to provide rooms for the educational service of the Institute : amphitheaters, offices and meeting rooms. As solar energy was one of the main research area of the Institute, a passive solar design was naturally selected in order to reduce the heating load of the building. A high thermal inertia was choosen by combining mass walls with a high thermal insulation level. It was decided to make the mass wall an advanced case study for IEA task XI in order to analyze the energy savings potential of such a system in the belgian climate.

The building has therefore been instrumented and monitored from June 88 to June 90. A second winter period was necessary because the auxiliary heating system and its control device did not work as expected.

The aims of the advanced case study were :

- to measure and analyze the performances of the built mass wall system,
- to propose an optimization strategy with respect to the requirements of both the user profile and the belgian climate. For that purpose, extensive computer simulations and parametric studies have been performed.

BUILDING DESCRIPTION [1]

Location

The building is situated in a peripheral area of Arlon, a small town in South Belgium. It has been built on a horizontal surface, close to a highway. There is no material obstruction to solar radiations until the end of the afternoon when the sun disappears behind surrounding buildings.

Form

The building has a rectangular (30 x 14 m) shape. This two-storied building is elongated from east to west and the southern facade has a trapezoidal shape with a maximum height of 10.75 m. The first storey consists of two amphitheaters enclosing a central hall. The second storey includes two meeting-rooms and several offices enclosing the same hall. The amphitheaters, offices and meeting-rooms are separated from the glazed south facade by concrete mass walls and narrow sunspace areas. The building cross-section is trapezoidal with a height continuously decreasing from 10.75 m (south facade) to 4 m (north facade).

Construction

The structure of the building is composed by load-bearing masonry walls with an insulating material (thickness = 12 cms) and a covering material for rain protection. The south-faced side is highly glazed : the glazed fraction is 66 % of the total southern facade. Concrete mass walls are situated behind the glazing and have both a thermal storage and a load bearing function. The north-faced side is insulated and consists of load-bearing concrete walls. The windows are double high emissivity glazing with aluminium frame. The insulating material of walls, roofs and floors is glass wool. The typical U-values in W/m^2K are 0.41 (floor), 0.28 (walls), 3.02 (windows) and 0.18 (roofs). This leads to an envelope heat loss factor of 1.6 kW/K for transmission through the fabric.

Services

The direct gain rooms are heated by solar radiation. The concrete walls provide short-term heat storage for amphitheatres, meeting rooms and offices and dampens the temperature fluctuations. Additionally, heating is produced by an auxiliary gas-fired boiler and distributed by thermostatically controlled radiators. In case of overheating or air pollution, ventilation automatically activated in amphitheaters and meeting-rooms. The glazed facade is provided with external roller-blinds which are activated during the night, in order to reduce the heat losses, and during overheating periods. No computer control of the building is provided even though the heating, ventilating and shading systems are partly automatically controlled.

Solar Features

The main passive solar feature consists of two mass walls situated in the southern facade and enclosing a direct gain central zone. Each mass wall is composed by a glazing with an external shading device, a buffer space and a thermal accumulation wall. The total glazing area is 135 m^2, representing 66 % of the south facade. The solar radiation is collected by the glazing and accumulated in the wall. Long-wave radiations are exchanged between the wall and the glazing and increase wall surface and air temperatures. The heat is slowly conducted through the wall and released, with a timeshift, to the rooms to be heated. The glazing is double without low-emissivity coating. The walls are painted white even though this colour is not optimal for the purpose of solar collection. The walls are composed by a combination of L-shaped concrete elements, separated between each other by interior windows. Additional interior windows are integrated in the concrete elements themselves at the second storey in order to provide some more daylighting in the offices and meeting-rooms. The external shading device is automatically activated during the night, during the weekend in winter and can be partly lowered manually by the occupants in case of overheating.Furthermore, the central part of the building works as a direct gain zone with a lot of solar radiation and heat storage in the walls, floors and concrete beams.

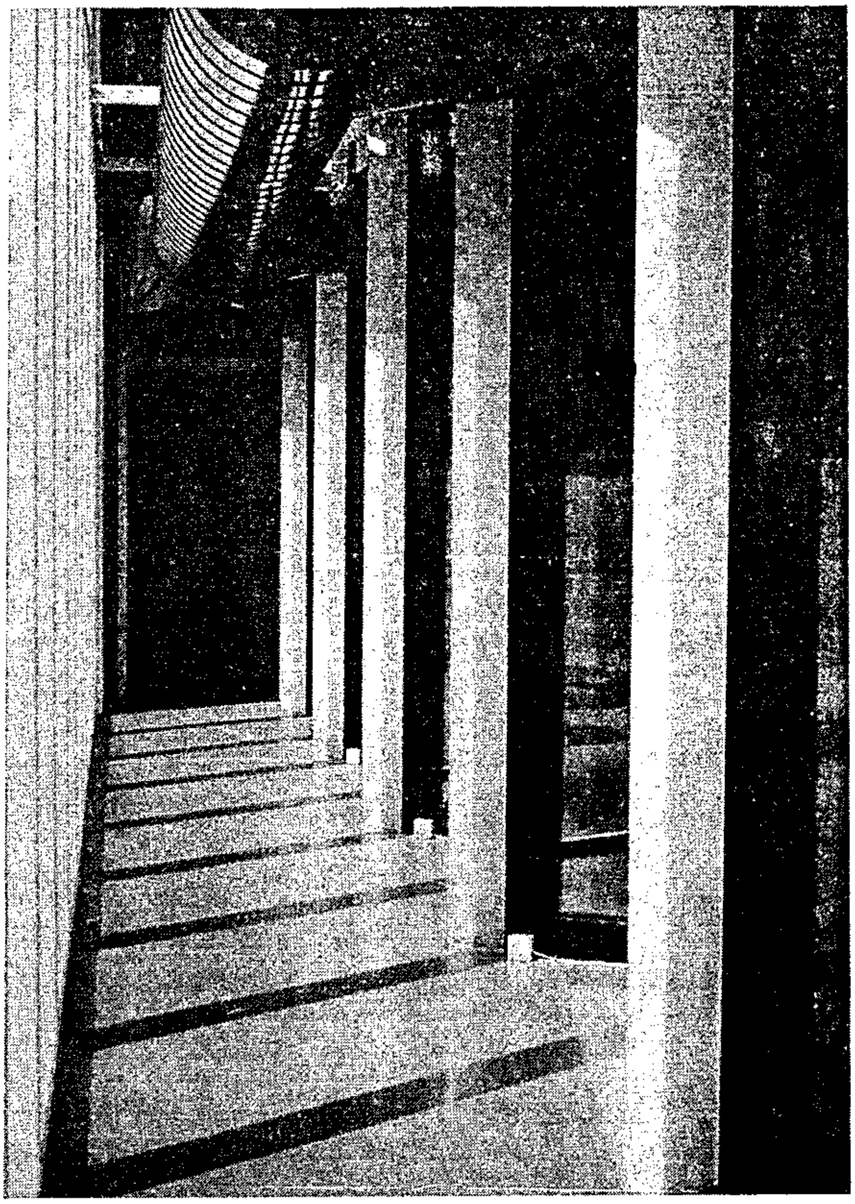


Fig. 1 : The mass wall of the FUL building

Thermal mass is present in the direct gain central zone as well : the floor and the ceiling are made of reinforced concrete and an additional concrete beam has been placed horizontal at the first storey, behind the glazing.The combination of thermal mass and high insulation level leads to a high thermal inertia characteristic for this building.

EVALUATION LEVEL

Objectives

The objective of the advanced case study was first to determine whether the building was working or not and to what extent the passive solar design of the building was responsible for the performance. Furthermore, the different components of the building, speciallly those concerned with the main passive solar features, ie. the mass wall, were to be investigated in details through extensive monitoring and computer simulation in order to detect whether their impact on the global building performance was optimal or not. This analysis had to lead to the formulation of optimized design guidelines for mass walls, considering different climates and user profiles.

Hypothesis

The main hypothesis at the basis of this work was the subdivision of the analyzed building in components closely related to their participation in the passive solar behaviour of the building. The detailed formulation of this subdivision is explained in [2] and can be summarized through the following enumeration of the components :

- "external" components : climate and occupants
- glazing and shading device
- buffer sunspace
- accumulation wall
- building zones
- building envelope
- auxiliary heating system
- mechanical ventilation system
- control system.

Experimental design

The experimental design has been selected in order to meet the requirements of the proposed analysis. The instrumentation of the building has been realized in conjunction with the different subsystems enumerated above. The glazing, buffer sunspace and accumulation wall received a special attention as they are the main passive solar features of the building. The detail of the monitoring plan is given in [3]. The monitoring period was first fixed to one year but several problems with the auxiliary heating system made a second year to be necessary in order to get reliable information from the measurements. Furthermore, some "one-time" measurements were planned : infrared thermographic analysis, pressurization test, heat fluxes measurements. These tests aimed at a better knowledge of how the building was responding to the action of environmental variables.

MEASUREMENTS

Objectives / Methods

The measurements were planned with the following objectives :

1. Evaluation of the thermal performance of the building. Investigation of the passive solar contribution of the mass wall to the heating load.

2. Validation of the belgian computer model "MBDSA" [11] against the data recorded in situ. This was useful in order to determine whether the software "MBDSA" was suitable for the simulation of passive solar commercial buildings including indirect gain and direct gain features.

3. Application of identification techniques for the determination of the thermal behaviour of a mass wall. The heat exchange coefficients of the transfer occuring in a mass wall were to be investigated as the values of these coefficients can be substantially different from those of a more classical design.

4. Evaluation, by means of a Fanger - like methodology, of the thermal comfort in the building.

In order to meet the these different objectives and following the division of the building into several subsystems, the a priori selection of measurement points considered :

- the division of the building in ten zones in order to allow the comparison of measurements with simulated results (a ten zones modelling was selected as well) ;
- the organization of the instrumentation according to the subsystems listed above.

The table 1 lists the measurement points, the building subsystem associated, the sensor which is used, the data acquisition periods and frequencies and the objective(s) the measurement aims at meeting. See [3] for further details.

Most of air temperatures were measured by "CTN" sensors (Fenwall UUA41J1). Kipp and Zonen pyranometers were used for the measurement of global and diffuse horizontal radiation. Special hot-wire anemometers were installed in the sunspaces for the measurement of air velocities. The gas (auxiliary energy) consumption was measured by recording the counter number twice a day. The same strategy was used for the global electricity consumption of the building.

Furthermore, a thermographic analysis of the building has been performed at several periods of the year by means of an infrared camera ("Hughes"). Some heat fluxes measurements have been realized with an "ETEL K-Therm" device. Finally, a pressurization test has been conducted in order to evaluate the infiltration losses of the building.

SUB-SYSTEM	MEASURED VARIABLE	CAPTOR TYPE	ACQUISITION PERIOD	ACQUISITION FREQUENCIES	OBJECTIVES
CLIMATE	Global horizontal external radiation	Solarimeter Kipp Zonen CM6	01/06/88 - 01/06/89	3 min / 15 min integration	3 4
	Diffuse horizontal external radiation	Solarimeter Kipp Zonen CM11/121	01/01/89 - 01/06/89	3 min / 15 min integration	[3] 4
	Beam external radiation				4
	External air temperature	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3 4
OCCUPANTS	CO2 pollution rate Zone 3				2 [3] 4
	CO2 pollution rate Zone 4				2 [3] 4
	Door status	Switch ON/OFF	01/09/89 - 01/06/89	15 min	[3] 4
GLAZING	Global horizontal internal radiation	Pyranometer Eppley	01/06/88 - 01/06/89	3 min / 15 min integration	3
	Outer surface temperature	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3
	Inner surface temperature	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3
SUNSPACE	Air temperature, module 1	CTN UUA41J1	01/06/88 - 01/06/89	15 min	[3] 4
	Resultant temperature, module 1	CTN UUA41J1	01/06/88 - 01/06/89	15 min	2
	Hot wire temperature, module 1	CTN UUT45J1	01/06/88 - 01/06/89	15 min	3
	Cold wire temperature, module 1	CTN UUT45J1	01/06/88 - 01/06/89	15 min	3
	Air temperature, module 2	CTN UUA41J1	01/06/88 - 01/06/89	15 min	[3] 4
	Resultant temperature, module 2	CTN UUA41J1	01/06/88 - 01/06/89	15 min	2
	Hot wire temperature, module 2	CTN UUT45J1	01/06/88 - 01/06/89	15 min	3
	Cold wire temperature, module 2	CTN UUT45J1	01/06/88 - 01/06/89	15 min	3
	Air temperature, module 3	CTN UUA41J1	01/06/88 - 01/06/89	15 min	[3] 4
	Resultant temperature, module 3	CTN UUA41J1	01/06/88 - 01/06/89	15 min	2
	Hot wire temperature, module 3	CTN UUT45J1	01/06/88 - 01/06/89	15 min	3
	Cold wire temperature, module 3	CTN UUT45J1	01/06/88 - 01/06/89	15 min	3
	Air temperature, module 4	CTN UUA41J1	01/06/88 - 01/06/89	15 min	[3] 4
	Resultant temperature, module 4	CTN UUA41J1	01/06/88 - 01/06/89	15 min	2
	Hot wire temperature, module 4	CTN UUT45J1	01/06/88 - 01/06/89	15 min	3
	Cold wire temperature, module 4	CTN UUT45J1	01/06/88 - 01/06/89	15 min	3
ACCUMULATOR	Outer surface walls temperature	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3
	6.25 cms depth walls temperature	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3
	12.50 cms depth walls temperature	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3
	18.75 cms depth walls temperature	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3
	Inner surface walls temperature	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3
	Concrete slab temperature	CTN UUA41J1	01/06/88 - 01/06/89	15 min	
PASSIVE DISTRIBUTION	Air temperature, Zone 2	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3 4
	Air temperature, Zone 3	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3 4
	Air temperature, Zone 4	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3 4
	Air temperature, Zone 5	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3 4
	Air temperature, Zone 6	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3 4
	Air temperature, Zone 7	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3 4
	Air temperature, Zone 8	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3 4
	Air temperature, Zone 9	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3 4
	Air temperature, Zone 10	CTN UUA41J1	01/06/88 - 01/06/89	15 min	3 4
	Resultant temperature, Zone 2	CTN UUA41J1	01/06/88 - 01/06/89	15 min	2
	Resultant temperature, Zone 3	CTN UUA41J1	01/06/88 - 01/06/89	15 min	2
	Resultant temperature, Zone 4	CTN UUA41J1	01/06/88 - 01/06/89	15 min	2
	Resultant temperature, Zone 5	CTN UUA41J1	01/06/88 - 01/06/89	15 min	2
	Resultant temperature, Zone 6	CTN UUA41J1	01/06/88 - 01/06/89	15 min	2
	Resultant temperature, Zone 7	CTN UUA41J1	01/06/88 - 01/06/89	15 min	2
	Resultant temperature, Zone 8	CTN UUA41J1	01/06/88 - 01/06/89	15 min	2
	Resultant temperature, Zone 9	CTN UUA41J1	01/06/88 - 01/06/89	15 min	2
	Resultant temperature, Zone 10	CTN UUA41J1	01/06/88 - 01/06/89	15 min	2
HEAT LOSSES	Infrared picture	Infrared camera	01/06/88 - 01/06/89	Occasionnaly	[3]
	Walls heat fluxes	Flux-meter	01/06/88 - 01/06/89	Occasionnaly	3
ACTIVE HEATING	Electrical consumption	Electrical counter	01/06/88 - 01/06/89	2 / day	4
	Gas consumption	Gas counter	01/06/88 - 01/06/89	2 / day	3 4
VENTILATION	Electrical consumption	Electrical counter			2 3
	" on " period	Grayphical recorder			4
WHOLE BUILDING	Electrical consumption	Electrical counter	01/06/88 - 01/06/89	2 / day	1
	Gas consumption	Gas counter	01/06/88 - 01/06/89	2 / day	1

Table 1 : Description of the monitored variables

Collection of measurement data

The data acquisition was performed by a Hewlett-Packard HP3421A system (up to 56 channels could be used), driven by a pocket calculator HP-41 CV via the HP-IL interface loop. The data storage was realized formerly on a HP cassette drive but this technique demonstrated not to be reliable. Consequently, an alternative technique was choosen, involving the use of a "PSION" hand computer to store the measurements on EPROM via a serial interface. During the first year of monitoring, the temperature measurements were performed and stored every 15 minutes while solar radiation measurements were scanned every 3 minutes and recorded after integration every 15 minutes. During the second year of monitoring, the storage period was raised up to one hour. Every one or two weeks, the data were transferred to a PC computer system on which the data processing was performed. Depending upon the objectives, this operation was realized by :

- a process identification software ("IDSOFT") developed at the FUL [4] in order to estimate heat exchange coefficients in a dynamical process ;
- a simple statistical software ("ANALYSIS") developed at the FUL in order to aggregate the information contained in the data ;
- a grahical software ("LOTUS") in order to visualize typical monitoring periods and aggregated results.

Energy

The table 2 lists the auxiliary heating load for the first four years of occupation of the building (October 1986 to September 1990). The monthly distribution of the auxiliary heating load is given in figure 2.

Heating season	Heating load GJ	 kWh
1986/1987	391	108587
1987/1988	357	99181
1988/1989	346	96198
1989/1990	349	97036

Table 2 : Heating load for 4 years

When reduced to gross floor area, these figures yield the values of the table 3

Heating season	Heating load / gross floor area MJ/m^2	 kWh/m^2
1986/1987	587	163
1987/1988	536	149
1988/1989	520	144
1989/1990	526	146

Table 3 : Heating load per gross floor area for 4 years

These figures can be seen as quite high for a passive solar building. The first year figure is probably the result of building drying and the consequence of a winter colder than the other years. The generally high level of the heating load is partly due to a bad control of the auxiliary heating system. Some measurements of the heating system itself have shown that the night and weekend setback strategy of the heating system was not effective, at least for one of the two distribution circuits. This comes from a lack of tightness of a three way valve which made the heating system work, even during setback periods. The monitoring pointed out the higher temperature of the southern circuit, compared to the northern one during setback periods.

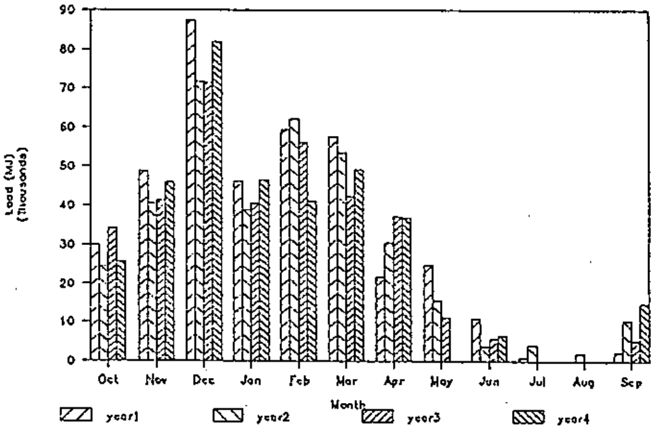


Fig. 2 : Monthly distribution of the auxiliary heating load (for 4 years)

Despite of the high insulation level of the building and the passive solar design, the heating load doesn't depict a good overall performance. Another explanation comes from the high value of infiltration losses. A pressurization test performed by the Belgian Building Research Institute [5] has shown the air renewal in different zones of the building to be :

-	Auditoriums :	0.3 vol / h
-	Meeting-rooms :	1.25 vol / h
-	Whole building :	0.65 vol / h.

All zones situated at the upper floor and consequently connected to the roof have a high infiltration rate due to the lack of an air tight layer in the roof.

Figures 3 and 4 show the correlation between the auxiliary heating load and respectively, the ambient temperature and the global horizontal solar radiation, calculated on the basis of monthly average values. Both correlations are not very strong (R^2 : 0.70 for the ambient temperature ; R^2 : 0.68 for solar radiation) and this relative weakness suggests that an external factor is influencing the energy consumption of the building.

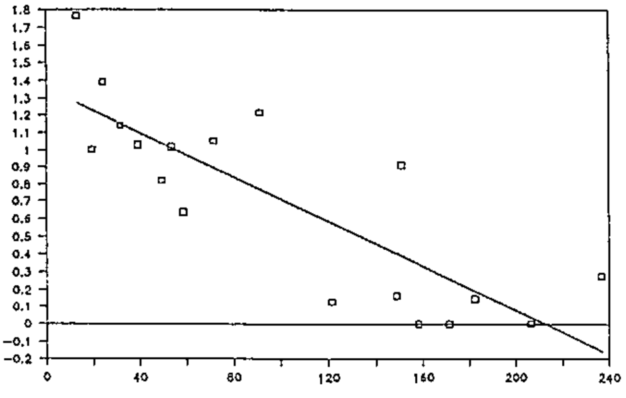


Fig. 3 : Correlation q aux / solar radiation

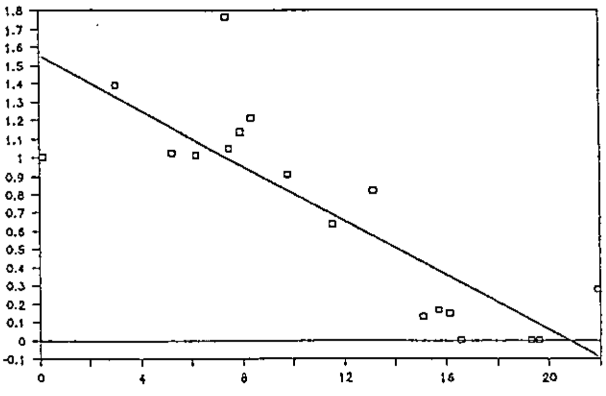


Fig. 4 : Correlation q aux /t ambient

Behaviour of the mass wall

The original passive solar heating device of this building has been selected as a chapter for the IEA task XI source book in the section devoted to "passive solar heating". Therefore, a special attention has been paid to this component in order to measure, analyze and understand the physical processes occuring in the concept.

A theoretical investigation of the mass wall, considered as a heating device has been performed and the detailed presentation of this approach is given in [6]. The physical processes occuring in the device have been identified and a simple but reasonably accurate model of the component has been built. The purpose of this modelling work was to serve as a mathematical support to perform an estimation of the physical parameters (heat exchange coefficients) of the device. Some results of this investigation have been presented in [7] and can be summarized as follows :

- The convective exchange coefficient at the surface of the mass wall in the sunspace, shows values between 5 and 9 W/m^{2}K (see table 4). The time variability of the parameters is clearly associated with the solar radiation level (figure 5).

Period	h_c (W/m^{2}K)
1	6.7
2	8.9
3	4.8
4	7.5
5	7.8
6	7.2
7	6.5
8	9.1

Table 4 : Average value of the convective exchange coefficient between the mass wall and the sunspace.

The values are generally higher than standard values for convection coefficients in buildings. The increase in the values is probably to be associated with the intensity of solar radiation reaching the wall, which includes thermocirculation effects in the sunspace, thus increasing the heat exchange. The results of the period nr 3 confirm this hypothese : this period is very poorly insolated (cloudy weather) and overcast conditions result in a substantial decrease in the intensity of the heat transfer process.

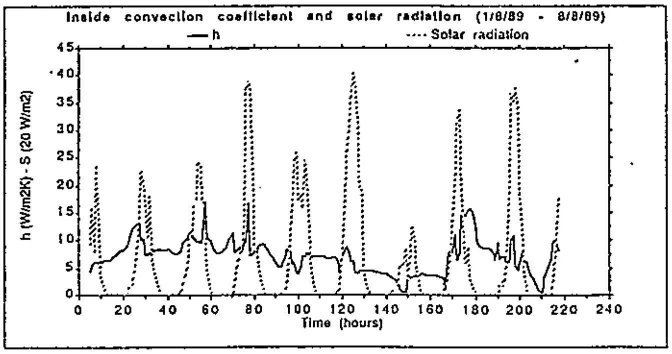


Fig. 5 : Time evolution of the convection coefficient between mass wall and sunspace for period nr 4.

- The thermal diffusivity of the L-shaped concrete wall is shown to be slightly different from values obtained by theoretical calculations. Indeed, theoretical calculations consider the wall as a one-dimensional medium : this means that the isothermal lines are assumed as parallels. This is probably not true because of the special design of the wall (see fig. 6).

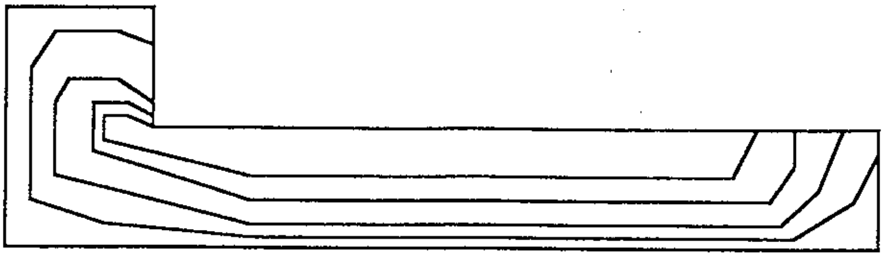


Fig. 6 : L-shaped mass walls and typical evolution of isothermal lines.

Nevertheless, the estimation procedure, based on a one-dimensional model, yields an equivalent thermal diffusivity which results in the same heat transfer process as if the wall was one-dimensional. The table 5 shows the value of the thermal diffusivity for different monitoring periods.

Period	Diffusivity (m^2/s)
1	1.15 10^{-6}
2	1.17 10^{-6}
3	1.20 10^{-6}
4	1.06 10^{-6}

Table 5 : Thermal diffusivity for several test periods.

These values have to be compared with theoretical values of the thermal diffusivity of reinforced concrete :

$$a = \frac{\lambda}{\rho c_p} = \frac{1.7}{2400.840} = 0.84 \ 10^{-6} m^2/s$$

The parameter estimation shows that a L-shaped mass wall, in which a two dimensional temperature field is likely to occur has to be simulated with an equivalent thermal diffusivity slightly higher than the theoretical values.

The overall contribution of the mass wall to the heating of the rooms situated behind it doesn't seem to be very significant. An estimation of the discharge flux of the wall to the auditoriums shows that this exchange is negative in winter and during cloudy days. Several reasons may explain the lack of performance of the wall :

- The wall is white. Consequently, most of the solar heat is reflected outside or on the floor.

- The wall is located too far form the glazing : the roof works then as an overhang device when the sun is high (fig. 7)

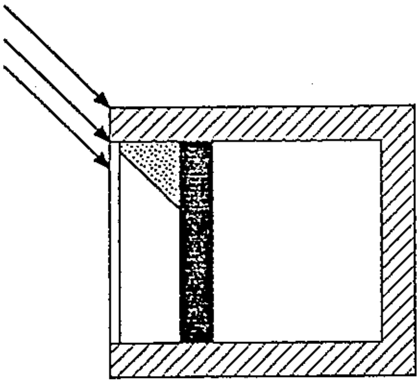


Fig. 7 : Overhang effect of the roof.

- The opaque part (34 %) of the facade works as a shading device with respect to the wall when the sun is far from southern azimuth (fig. 8).

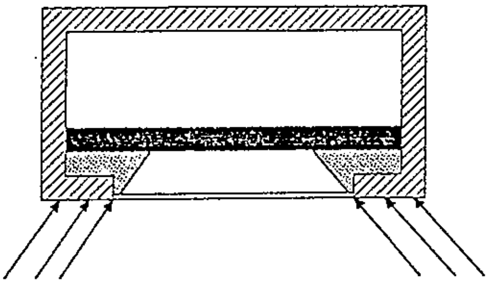


Fig. 8 : Shading effect of opaque parts of the wall.

- Ventilation ducts are situated in the sunspace. They are painted red and , consequently, absorb more solar energy than the wall itself. Furthermore, they act as a shading device for the wall (fig. 9).

Fig. 9 : Shading effects of ventilation ducts in the sunspace.

A general impression, when looking at the wall at several periods of the year, is that the wall is very poorly insolated, because of the several reasons enumerated above. This should have been taken into account in the design.

Finally, an investigation of the response of the mass wall to, respectively, solar availability and external temperature, can be performed by the calculation of correlation coefficients between the measured mass wall temperature and, respectively, global horizontal solar radiation and external temperature. The two correlations are shown (fig. 10 and 11) and yield the following regression coefficients, on a monthly average basis :

- wall temperature / external temperature :	0.91
- wall temperature / solar radiation :	0.81

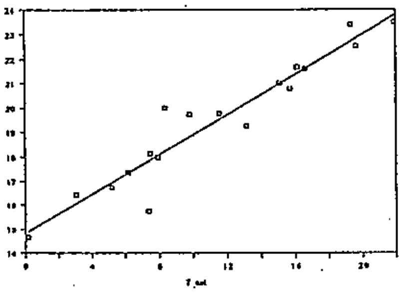


Fig. 10 : Correlation t wall/t ext.

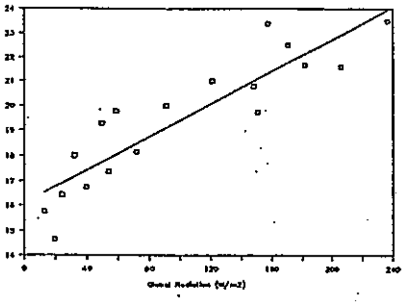


Fig. 11 : Correlation t wall / solar

These calculations and pictures show that the wall seems to respond more to external temperature than to solar radiation. The mass wal is therefore suspected to work more as an insulating device than as a solar collection feature in the belgian climate.

Comfort (Amenity)

The air temperature has been recorded in every zone of the building. Averaging the recorded values for two years of monitoring yield the following figures (table 6).

Zone	Average temperature (K)	Standard deviation (K)
Auditoriums	19.5	0.8
Central hall	21.5	2.3
Offices	21.7	1.5
Visitors offices	22.7	2.0
Meeting-rooms	20.7	1.4

Table 6 : Average temperature and standard deviations for some zones.

This table shows that the average temperatures in the building are quite high, considering the setpoint of the auxiliary heating system to be 21°C during the day. The auditoriums are the coldest zone of the building (because of the reduction of the direct gains) with the lowest deviation around the mean, indicating the damping effect of the mass wall. All solar insolated zones exhibit average temperature above 20°C with large deviations around the mean, due to both direct solar gains and heating setback. The peak (minimum and maximum) values of the temperatures in the same zone are indicated in the following table (table 7).

Zone	Minimum temperature(K)	Maximum temperature (K)
Auditoriums	13.5	27.5
Central hall	14.6	35.7
Offices	14.3	31.3
Visitors offices	16.9	35.8
Meeting-rooms	13.5	30.1

Table 7 : Minimum/maximum temperatures for different zones.

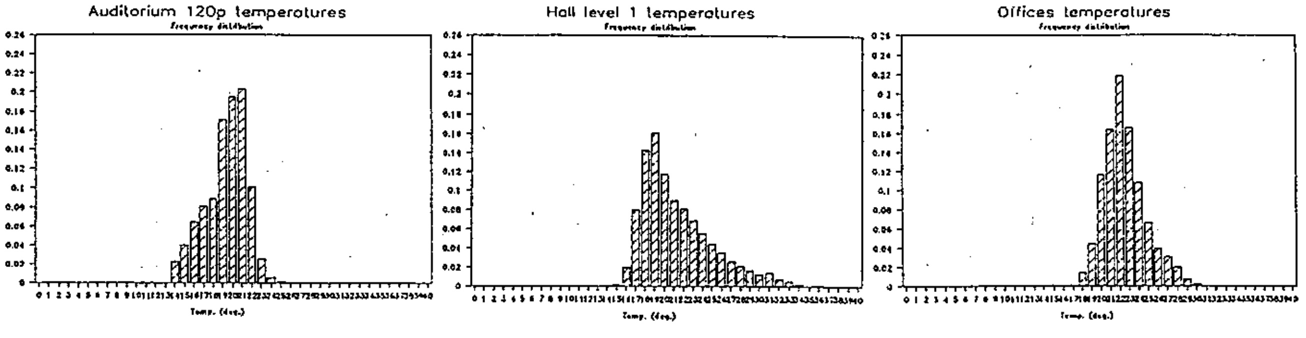
The minimum values are usually associated with the night and weekend setback (although not entirely effective) of the auxiliary heating system while maximum values are the result of a high solar radiation level. These values are usually high, specially if we consider that the rooms are occupied and this shows that overheating is a major problem in this building.

The overheating trend can be investigated by the computation of temperature frequency distribution diagrams. The figure 12 shows such diagrams for several rooms. Indirect gain zones (auditoriums) exhibit distributions centered around the heating set point and including more underheating than overheating. Direct gain zones show diagrams displaced to the right with a large amount of overheating hours. The calculation of the overall overheating frequency for several typical zones of the building yields the figures of table 8.

Zone	Overheating frequency (%)
Auditoriums	0.8
Central hall	24.1
Offices	27.5
Visitors offices	35.1
Meeting-rooms	14.8

Table 8 : Overheating frequency for different zones.

This table shows that overheating occurs during a large proportion of occupation hours in the directly insolated zones. Even though the building occupants have the possibility to lower roller blinds in case of overheating feeling, they don't use them very often, probably because they want to keep in touch with the surroundings and to benefit form the daylighting associated with solar radiation. Openable windows are located in the roof of the offices area and occupants could use them in order to increase the infiltration rate of the rooms. But they don't use them very often either. To reduce these overheating problems, an additional mechanical ventilation system has been installed in the offices area. Again, the occupants don't use it because of the noise created by the ventilators.



Auditoriums Hall Offices

Fig.: 12 : Frequency distribution for typical zones.

SIMULATIONS

Objectives

The objectives of the simulation work performed in the context of this project were twofold :

1. To validate and/or calibrate a computer model that could be used as a reliable tool for the simulation exercise.
2. To use a reliable tool in order to perform a systematic analysis of the building in order to establish whether the design is accurate and to derive optimal design guidelines considering both energy and comfort related evaluation criteria.

Models used

Suncode [12] is a well-known design tool specially developed for passive solar applications. However, the Laboratory of Thermodynamics of the University of Liège (Belgium) has developed a multizone building dynamic simulation program (called "MBDSA" [11]) and the program designers were very interested in the application of this model to a passive solar commercial building in order to know whether the product was accurate for modelling this type of building. Consequently, both models have been used in a first step, which concerned the validation of the program.

Validation / Calibration

A preliminary work has concerned the validation of MBDSA against in situ measurements and a comparison with the predictions of the SUNCODE program.. Therefore, two typical periods have been selected, one in winter (from 04/02/89 to 10/02/89) and one in summer (29/07/88 to 05/08/88). Both test periods exhibit very different features. The winter period was cold and foggy while the summer one was hot and sunny. This was intended to demonstrate the validation of the code for opposite weather conditions.

The detailed results of the validation exercise are available in [8] and will not be reproduced here. Only the main conclusions of the procedure will be drawn.

- The winter simulations have showed the big influence of the modelling of the heating system. Most of the unaccuracy of the modelled results can be due to the poor a priori knowledge of the behaviour of the auxiliary heating system. It's almost impossible to conclude about MBDSA temperatures accuracy without a good knowledge of the net energy input to all zones. Nevertheless, the program appears as a good design tool to compute the heating load of a building.
- The summer simulations have showed the generally god accuracy of the MBDSA results compared to the measurements. This accuracy remains very good for the sunspaces in which special thermal processes are occuring. This points out the fact that MBDSA is a well suited design tool for all buildings including passive solar buildings.

After the publication of [8], an additional validation exercise has been performed on the data of 18 days of August 89 (from 01/08/89 to 18/08/89). This additional test confirmed the results of [8]. Moreover, a special attention has been paid to the dynamical behaviour of the mass wall by considering the evolution of the surface temperatures. The comparison of surface temperature on both sides of the wall shows an excellent agreement between the model and the measurements (fig. 13).

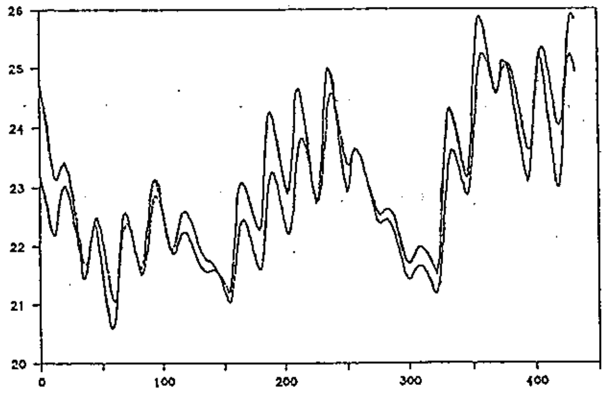


Fig.13 : Wall surface temperature (MBDSA vs measurements).

Consequently, the validation of MBDSA for this building is agreed upon and, furthermore, can be improved by using some results of the identification procedure for the selection of accurate values of some physical parameters (see above: "Behaviour of the mass wall").

Input and assumptions

After validation and calibration, MBDSA has been recognized as a reliable tool in order to perform a systematic parametric analysis of the building. The detailed description of the building file is given in [8] together with the different assumptions realized for fitting the building into the model.

Results

The program MBDSA has first been used for a systematic parametric analysis of the building. The parameters that were investigated are the following :

- the orientation of the building
- the glazing type
- the buffer space geometry
- the mass wall absorption properties
- the mass wall thickness
- the roller blinds activation strategy
- the south facade glazing area
- the ventilation rate across the wall
- the insulation of the wall
- the storage material
- the climate

The evaluation criteria that allow the comparison of different designs were choosen as :

- the total heating load for the evaluation of the energy savings
- the number of overheating hours in the offices (the most frequently occupied zone of the building) for the evaluation of thermal comfort.

The comparison of the variations has been performed with respect to two special designs :

1. The "base case" : the real (as built) FUL building design. The comparison between a given variation and the base case leads to the optimization of the passive solar system.
2. The "reference case" : the design of an equivalent building (same volume, floor area, architectural shape) realized according to the belgian construction standards (insulation level, fenestration, ...) but without any special passive solar features.

The detailed presentation of most of the results is given in [9]. Additional results are provided in [10]. The main conclusions of the analysis are as follows :

The energy optimum design of a mass wall in the belgian climate should include :

- a south orientation
- a double low-e glazing
- a narrow buffer space (wall and glazing close to each other)
- a black wall
- a 25 % glazed ratio in the south facade
- a night activation of roller blinds
- an optimized control strategy of the heating system.

The figure 14 shows the monthly heating load for 3 designs (reference, base and optimized).

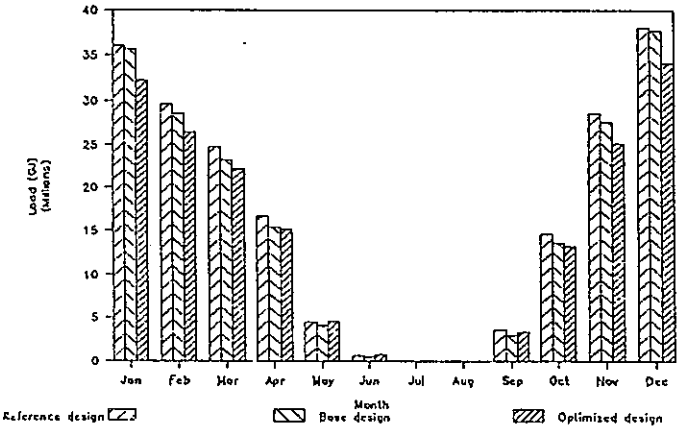


Fig. 14 : Heating load for 3 designs

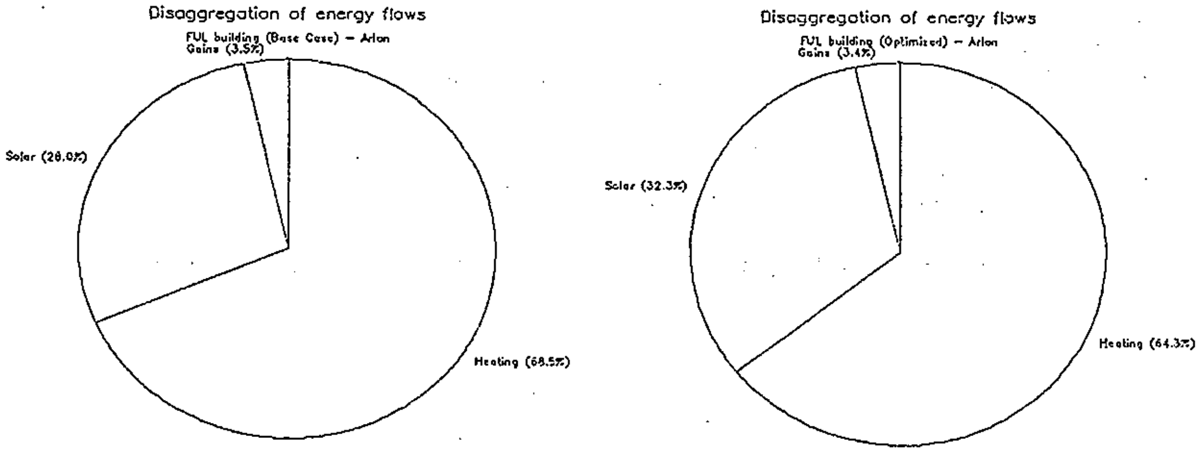
On the other hand, this optimum design yields the weakest level of comfort and the designer has to compromise between both aspects.

The simulation has also been used in order to give an estimation of the passive solar contribution to the heating load of the building. Therefore, the following procedure has been applied : the building is simulated twice. First it is simulated with actual and complete weather data. Then, the same building is simulated with a special weather data set in which all insolation values (global, direct and diffuse) are set to zero. This yields the performance of the building if they were no sun. The comparison of the heating loads in both cases yields the solar fraction of the building. The same procedure has been performed for both the base case and the optimized case (resulting of the parametric analysis). The following solar fractions are obtained :

Case	Solar fraction
Base	0.29
Optimized	0.33

Table 9 : Solar fraction for two designs.

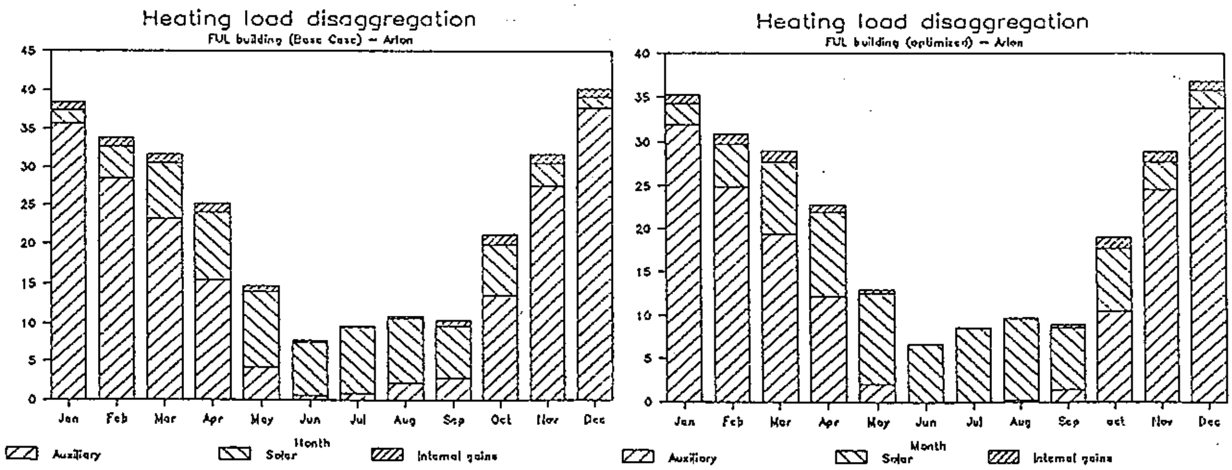
The computation also allows the yearly and monthly disaggregation of the energy fluxes (auxiliary, solar and internal gains). They are showed in figures 15 and 16 for two designs (base case and optimized design).



Base design

Optimized design

Fig. : 15 : Yearly disaggregation of fluxes for two designs



Base design

Optimized design

Fig. 16 : Monthly disaggregation of fluxes for two designs

CONCLUSIONS

Measurements

Measurements on the FUL building show that this building doesn't work as it should. The passive solar contribution to the heating load is reduced by several design mistakes. The mass wall doesn't collect enough energy and the glazing quality is too poor to keep the solar gains inside the sunspace. Consequently, much of the solar gains entering the sunspaces are lost either by the wall itself (reflexion towards outside, or by the glazing or by the ventilation ducts (heated by the sun and cooled by the air pushed outside). The behaviour of the wall is nevertheless satisfactory in summer when it works as a damping device for the temperatures inside the auditoriums.

The auxiliary heating system doesn't work satisfactorily during the set back period. The problem has been located (bad functioning of a 3-way valve) but has not been solved yet. More generally, an optimization of the different control systems (heating, venting, shading) should be performed in order to improve the passive solar behaviour of the building.

Overheating is a major problem in this building as well, specially at the upperfloor where the direct gain contribution is much more important than at the ground floor. Temperature rises up to 35° have been recorded and most of the cooling devices (shutters, windows, ventilation) are shown not to be appreciated by the occupants.

Simulations

Simulations of the FUL building have shown the theoretical solar fraction to be 29 %. This is not so a bad result. A survey of the different parameters that influence the performance of the building and a systematic parametric analysis yield an optimization of the design. This optimized design results in a 15 % energy savings compared to the base case. Once optimized, the building performs well, with a theoretical annual heating load close to 240 MJ/m^2 gross. Considering 70 % heating system efficiency, this results in an estimated load of 340 MJ/m^2 gross, a good performance for a passive solar building in the belgian climate.

Synthesis

This analysis has shown that a good combination of experimental results and computer simulation could work as a method for defining the optimum design of a mass wall building in the belgian climate. Simulations allow extrapolations to be made of what has been measured while measurements establish a link with the real world. As a conclusion, it seems possible to design a mass wall building in the belgian climate that will exhibit an annual heating load of less than 350 MJ/m^2 gross floor area.

RECOMMENDATIONS

When designing a mass wall building in the belgian climate, the architect should pay attention to :

- the orientation of the building : south is the best
- the glazing quality : double low-e glazing is required
- the buffer space geometry : place the wall just behind the glazing
- the wall color : black is recommended
- the overall control system of the building : heating, venting and shading strategies should be optimized in order to maximize the passive solar contribution.

Furthermore, the architect should avoid :

- to install ventilation ducts in the sunspace
- to create additional overhanging effects with the roof.

Finally, installation of useful (and usable), cooling stragegies (shading, venting, ...) should be performed if the building works as a direct gain system as well.

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SCHOPFLOCH KINDERGARTEN
Direct Gain and Collector Air Heating System

Fig.1: A view of the Schopfloch Kindergarten from the south-east

ABSTRACT

The Schopfloch Kindergarten was designed as a single-class kindergarten with a gymnastic hall by the architect Bela Bambek. It is a single-storey flat roof building with a shed in east-west direction over the whole roof. With total glazing on the north side the shed helps daylighting the rooms and is provided with air-collectors for space heating on the southern slope. The large glazed walls on the west, south and east front of the building offer a nice view of the green surroundings. Using air collectors (38 m^2) and a 20 m^3 rock-bed storage the heat stored over the day is used to heat the building during the night and the next morning. The hot air floor and wall heating system is an old Roman structure, called "Hypokaustenheizung". It was shown that this cheap system - with integrated collectors on the roof - works well, provided the control system is precisely adjusted. The overhangs of the roof could not prevent overheating in the gymnastic hall which is facing west, during the afternoons in March and April.

INTRODUCTION

The kindergarten was planned with regard to high gains of passive and active solar energy. The light building construction allows for fast space heating through direct gains and is a precondition for a quickly reacting auxiliary heating system. The system has been set up as a hot air floor and wall heating system, using the advantages of low heating temperatures without having the disadvantages of a direct air heating system - such as dry air or air movements. The project was chosen as an Advanced Case Study to examine the combination of a passive solar energy system - with direct heating - and an active system with air-collectors and storage.

To be able to use the active system, it had to be reconstructed first. A pipe had been wrongly laid by the company installing the system (the company not having had prior experience with solar energy systems and obviously not fully understanding this system). Therefore the storage could only be charged but it could not be discharged. During the reconstruction works an extensive measuring system was also installed, and in November 1988 the detailed measurements began.

The goals of the Advanced Case Study were:

- recording the behavior of the system and its components (collector, storage, glazing)
- developing suggestions for improving the control system after analysis of the first heating period
- to examine the occupants' reaction to this 'solar' building

Fig.2: A view from the gymnastic hall to the west in the late afternoon

BUILDING DESCRIPTION

Site and location

The building is located in Leonberg-Ezach (- approx. 15 km to the west of Stuttgart) in the centre of an area with newly erected buildings. The site is 400 m above sea level, has a slope of 2.5% from north to south and is - except for the old kindergarten in the northern part of it - till now undeveloped.

Building form

The one-storey building has a square ground area, using the corners as an outdoor playground. From the south the visitor enters into a central atrium which serves as a cloakroom and additional indoor playground during raining periods. The two group rooms are located on the east side of the building and the western part is the gymnastic hall. Material, service and sanitary rooms are situated on the north of the kindergarten. The U-shaped rockbed storage, divided into two chambers, has a central position in the building. Its losses - heat transmission through the 100 mm thick insulation - are passive gains for the surrounding rooms.

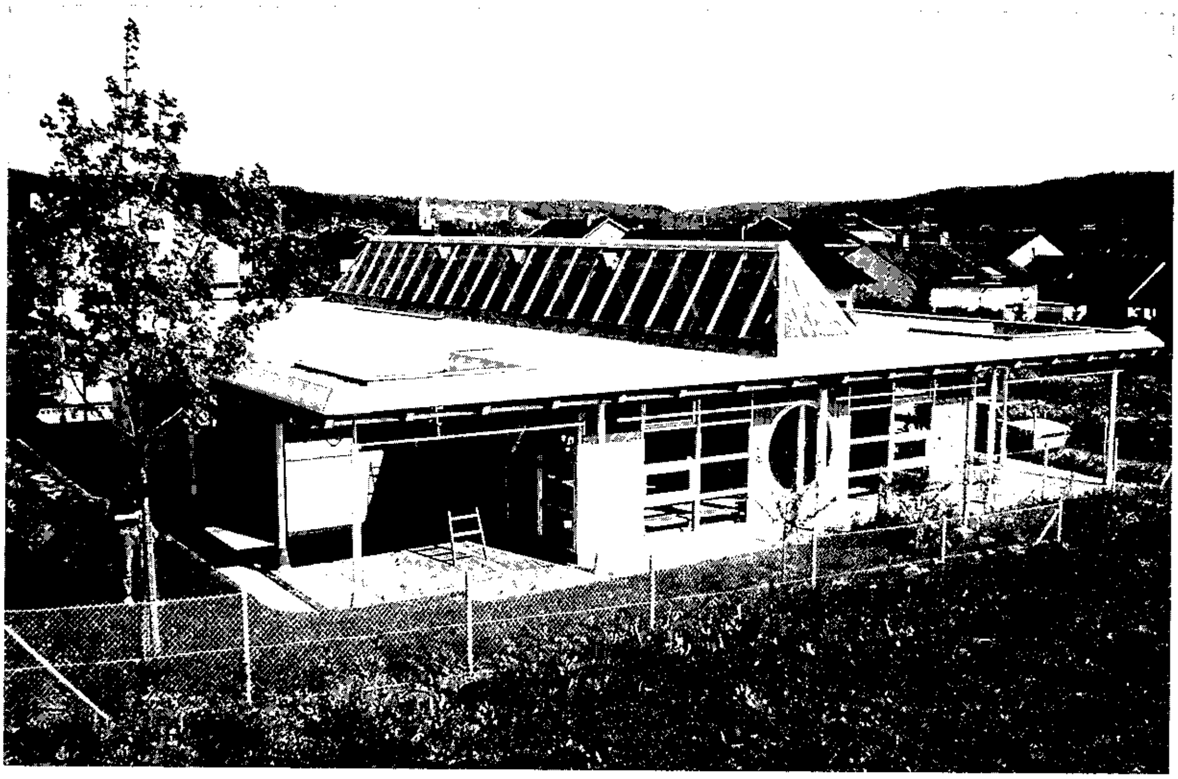


Fig.3: The Schopfloch Kindergarten seen from the north-east

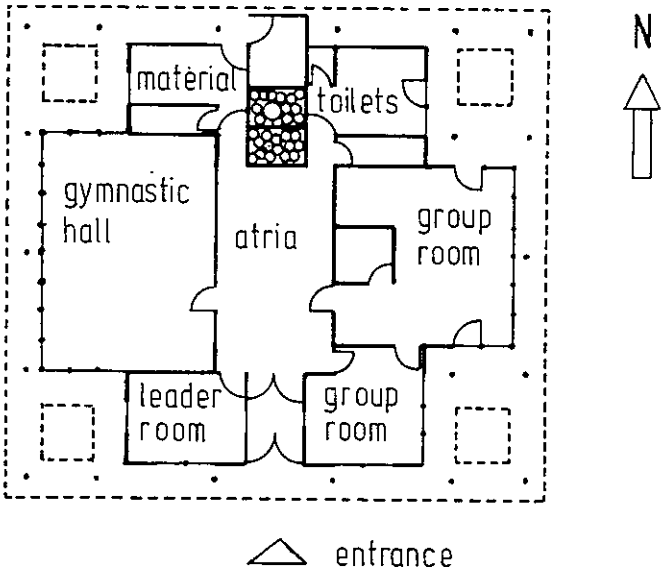


Fig.4: Cross section of the building

Surface Areas:

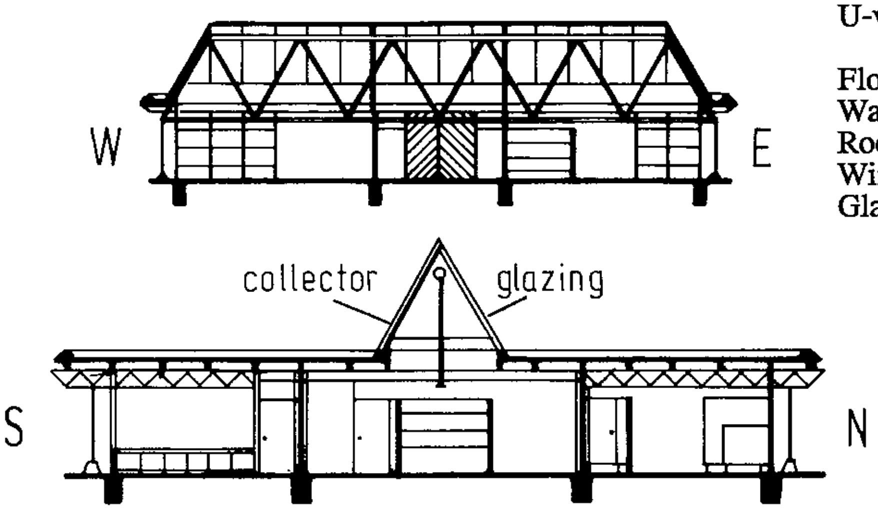
Ground floor:	270 m^2
Envelope:	638 m^2
Walls:	200 m^2
Windows:	157 m^2

Function

25 children and 2 kindergarten teachers use the building. Kindergarten hours are from 8 a.m till noon and from 2 - 4 p.m. A large garden area to the east of the building and the gymnastic hall provide lots of space for the children to play in regardless of weather conditions.

Building construction

The Schopfloch-Kindergarten is a steel construction with prefabricated wall elements. The elements are a double shell wood construction including a 80 mm rockwool insulation. The inner surface has a sound reductive coating. The windows and the glazed wall elements are timber framed with double glazing. The total heat loss coefficient of the building - transmission and infiltration losses - is 615 W/K and is due to the spacious glazing area.



U-values: W/m^{2}K	
Floor:	0.59
Wall:	0.45
Roof:	0.34
Windows:	
Glass and frames:	3.0

Fig.5: W-E and N-S cross section of the building

The shed-type roof is a self-supporting steel construction with insulating glazing on the northern slope. The southern slope serves for mounting air collectors with a timber frame construction. The black plastic absorber foil is mounted on a 10 cm insulation and the 15 cm air gap is double covered. These covers are Polytetrafluoräthylen foils (Hostaflon) with a thickness of 50 μm inside and 150 μm outside. The transmission coefficient of these covers is τ = 0.9 for the solar radiation and τ = 0.02 for a thermal radiation in the range of 50 °C. This means that the covers are nearly opaque for the collector's operating range and that the collector suffers almost no losses through radiation.

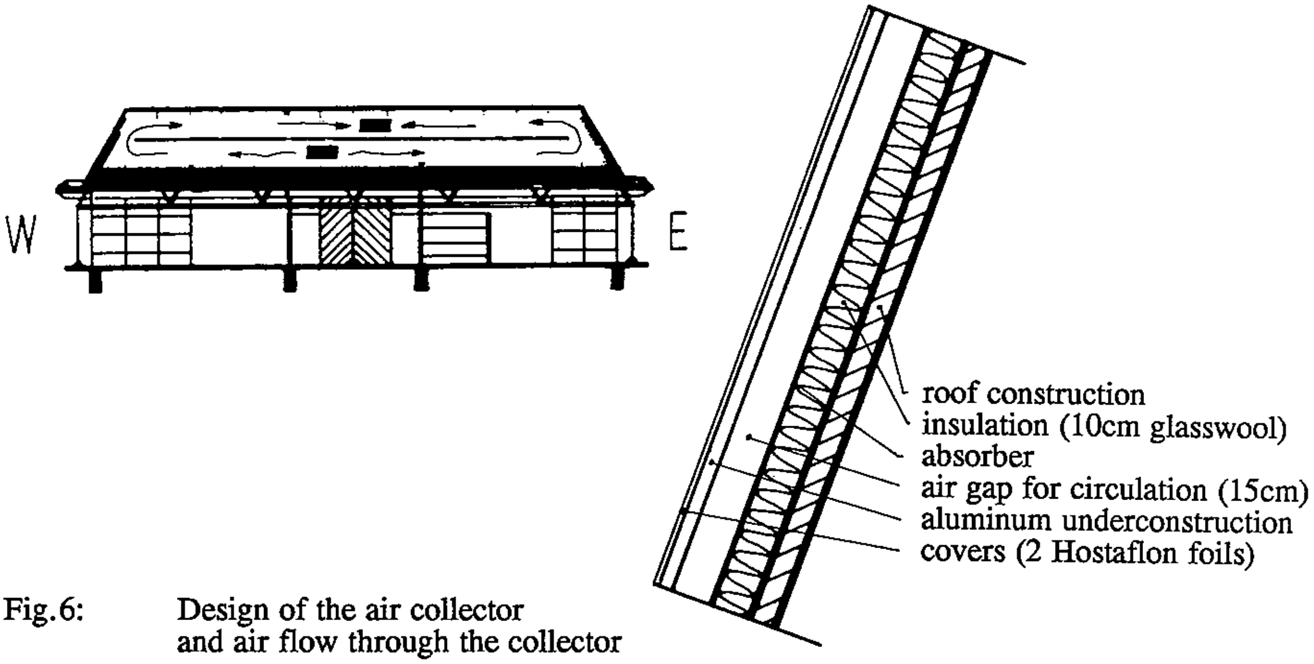


Fig.6: Design of the air collector and air flow through the collector

Services

The floor and parts of the inner walls are the heating areas of a hot air heating system. The construction of the heating areas is sketched in fig.7. This system type was chosen by the architect to ensure that the air collector and the rockbed storage could be included without problems.

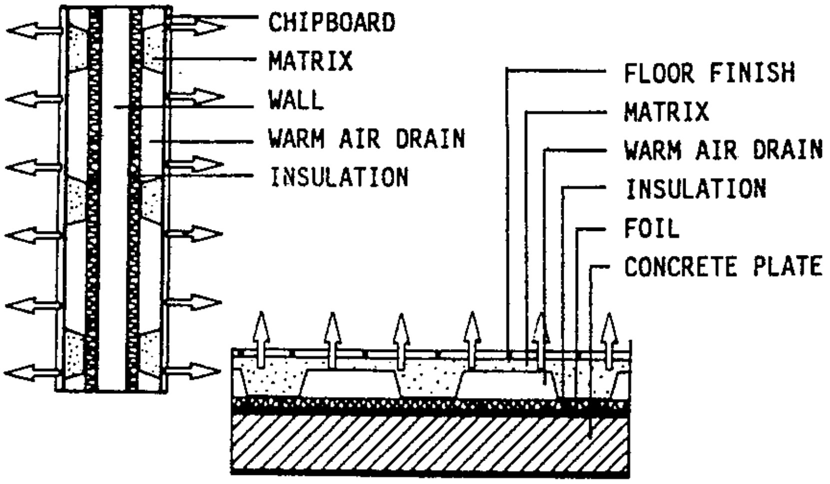


Fig.7: Construction of wall and floor heating elements

On the basis of the design, the size of the auxiliary gas boiler was determined for a capacity of 24 kW. To distribute the hot air in the Hypocaust-heating system a fan with a 2.0 kW electrical engine was installed.

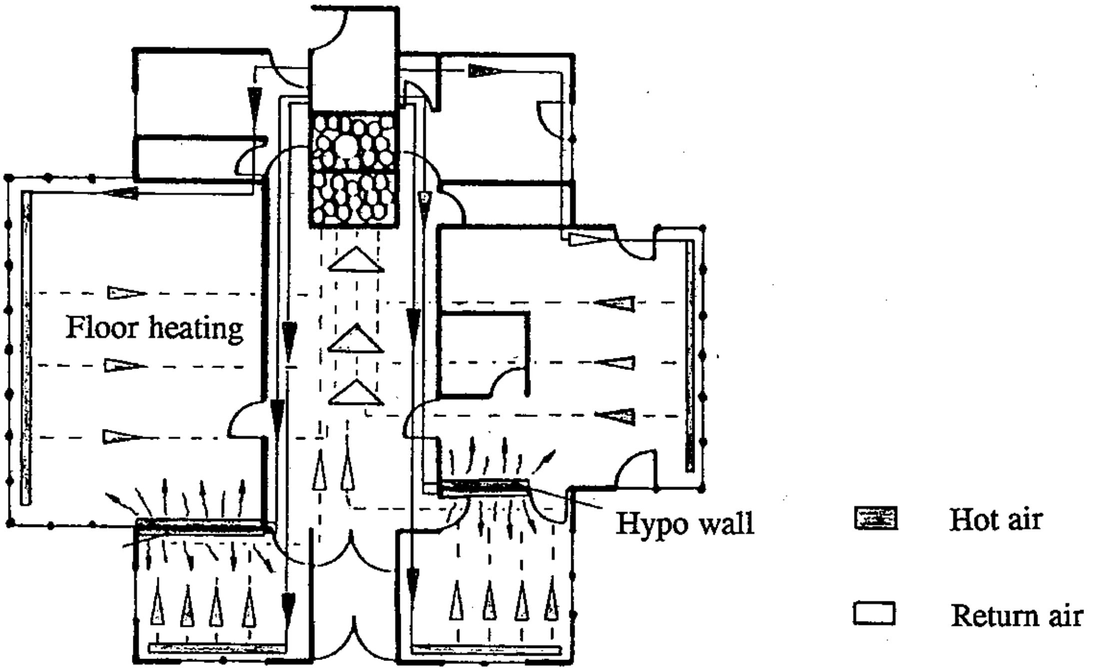


Fig.8: Distribution system of the wall and floorheating system

Fig.8 shows the distribution system with the incoming ducts for the hot air near the external walls and the collecting duct for the return air in the atrium. The two hypocaust walls are connected seperately providing the facilities for an overheated inlet.

SOLAR SYSTEMS

Passive system

The large slope of the shed-roof facing north with a glazing area of about 40 m^2 and a white diffusely reflecting inner surface on the southern slope give the rooms maximal daylight without overheating them. The overhang of the roof (ca. 1.20 m) partially shades the large glazed wall surfaces on the east, south and west and was designed to avoid overheating of the rooms in summer. It was redesigned to make additional shading devices superfluous. This can only be corrobareted for the south orientation.

Window data:	Glazing factor =	glazing/exterior surface	U-value:
	east	70%	3.0 W/m^{2}K
	south	52%	
	west	52%	Frame ratio:
	north	31%	0.35

The glazing factor for the north side includes the northern shed glazing, which is a low e glazing with an U-value of 1.3 W/m^{2}K.

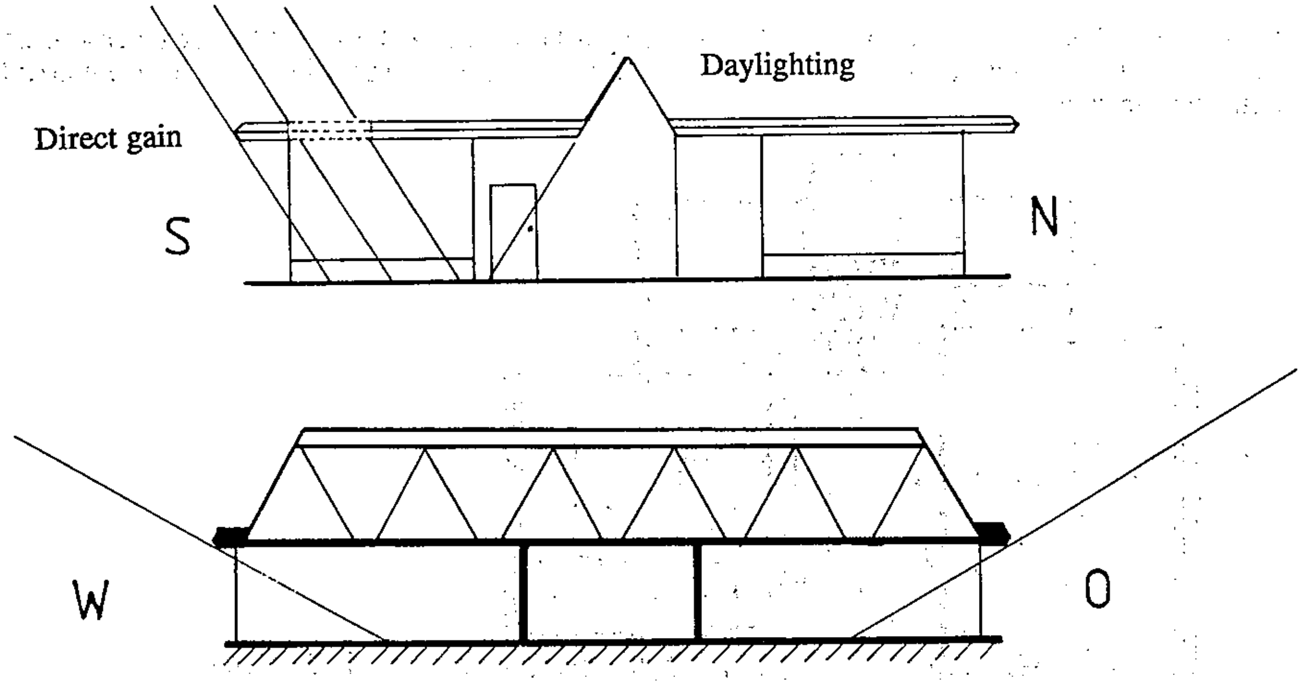


Fig.9: Passive system for direct heating and daylighting

The very light construction of the building supports a quick upheating by direct solar gains (compare fig.25). On the other hand, the large glazing areas of 160 m^2 create high transmission losses and overheating problems in the transitional periods.

Active system

Air collectors:	Absorber area	38 m^2
	Air flow	35 $m^3/h\ m^2$
	Collector fan	0.25 kW
Storage:	Volume	20 m^3
	Capacity	40 MJ/K = 11 kWh/K (including concrete walls)
	Material	Serpentinit
Service:	Auxiliary heating	100 W/m^2 = 24 kW total
	Heating fan	
	1. step	0.5 kW
	2. step	2.0 kW

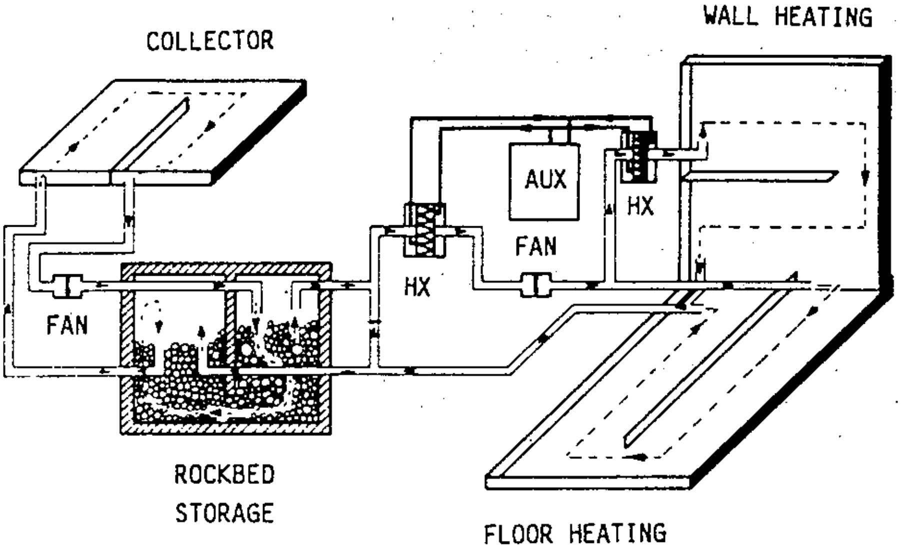


Fig.10: Scheme of the solar assisted heating system

The space heating system of the kindergarten was designed for the direct use of solar collector gains (38 m^2) for the floor and wall heating. Direct heating without storage is possible. If the collector output is lower than the heat demand, a gas driven auxiliary heater supplies heat to a water-air heat exchanger. Solar gains which are not needed for heating are stored in a rockbed storage consisting of Serpentinit rocks - grain size ca. 50 mm -. An additional water-air heat exchanger allows an overheating of the wall surfaces to heat up the rooms quickly in the morning. Air tight flaps in the charging and discharging ducts of the storage were installed to prevent an uncontrolled discharge to the collectors or the heating system.

Control system

The whole heating and active solar system is controlled by a programmable control device. Heat from the air collectors or from the storage is prefered to heat from the auxiliary heating system. The hot air is additionally heated if the actual inlet temperature deviates from the set point, which is influenced by the ambient temperature. The additional surplus-heater for the wall inlet air is activated if the room temperature drops below 19.5 °C. A sensor in the outlet pipe of the floor heating system measures the air temperature of the outlet flow and the controller opens a bypass flap if this temperature is higher than the maximum storage temperature. Manually controlled ventilation flaps in the northern slope of the shed-roof allow an individual conditioning in summer according to the users' requirements.

MEASUREMENTS

Objectives / Methods

The measurements were designed to:
- record the behavior of the system and its components
- examine the system's effects on the occupants' comfort

Therefore an extensive measurement system was installed in Ezach Kindergarten. The following values were collected during the last heating periods 88/89 and 89/90.

Climate:
- ambient air temperature
- global radiation on the collector surface

Building:
- air temperature in various rooms at different heights

Collector:
- temperature at the air inlet and outlet of the collector
- velocity of the air flow at the collector outlet
- absorber temperature
- optical material data of covers and absorber

Storage:
- storage temperature at three points
- flow velocity at storage discharge
- inlet and outlet temperature at storage discharge

System:
- supply air temperature of the floor heating system
- supply air temperature of the wall heating system
- exhaust air temperature of the floor heating system
- status of the heating fan
- status of the collector fan
- power consumption heating fan
- power consumption collector fan
- gas consumption of the auxiliary heating system
- amount of heat provided by the auxiliary heating system
- total current consumption

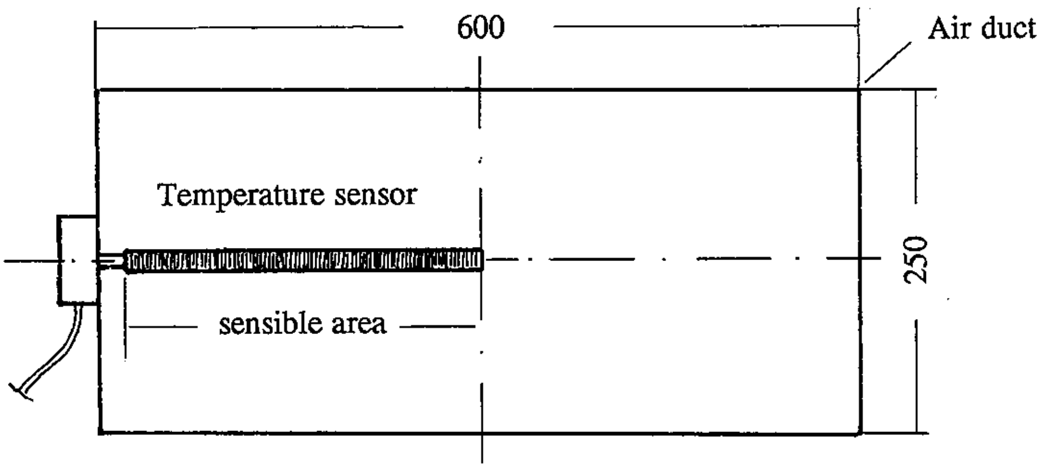


Fig.11: Integral air temperature measurement by special PT 250

The temperatures in the air heating sytem were measured with special PT250 temperature sensors which allow an integral measurement over the flow cross-section. Velocities of flow were permanently measured by fixed miniature impeller-fan-wheel-anemometers after the flow profiles had been determined. Together with the gas counter an ultrasonic calorimeter in the heating water cycle between the gas boiler and the water-air heat exchanger allows an efficiency determination of the boiler. Two additional current counters were installed to determine the current consumption of the collector and the heating fan.

Collection of measurement data

Data from the numerous measuring instruments were digitized by a scanner with an intergrated A/D tranducer (by Hottinger Baldwin Meßtechnik, Stuttgart) and transfered to a XT Personal Computer. The measured results were recorded every minute, using a measurement program written in Basic. The computer saved only the hourly mean values. A 30 MByte hard disk was used to store the data. This data storage proved to be useful, particularly for the volume of data made up of minute values that were recorded over a period of 14 days in December. The recorded measured results were analyzed by table calculation programs processed through graphic programs and then printed out. In addition the kindergarten teachers recorded the values of the gas counter and the current meters daily at 8 a.m and 4 p.m.

Measurements at the collector

Analysis of the collector temperatures showed considerable differences between the temperature at the inlet and the outlet during the day as well as in the night in a negative sense. Figure 12 shows that at night while the storage was discharged cold air was sucked from the collector into the storage. The difference in temperature ranges up to 10 Kelvin. This air flow was caused by "airtight" ventilation flaps between collector and storage. Through readjustment the flaps could partly be stuffed yet it is important that airtight flaps with felt bonds should be used. An air leakage rate of 13% was determined by measurements in the air inlet and outlet duct of the collector. This shows the necessity of air collectors in the suction operation. Determining the collector's thermal efficiency this air leakage fraction has to be considered.

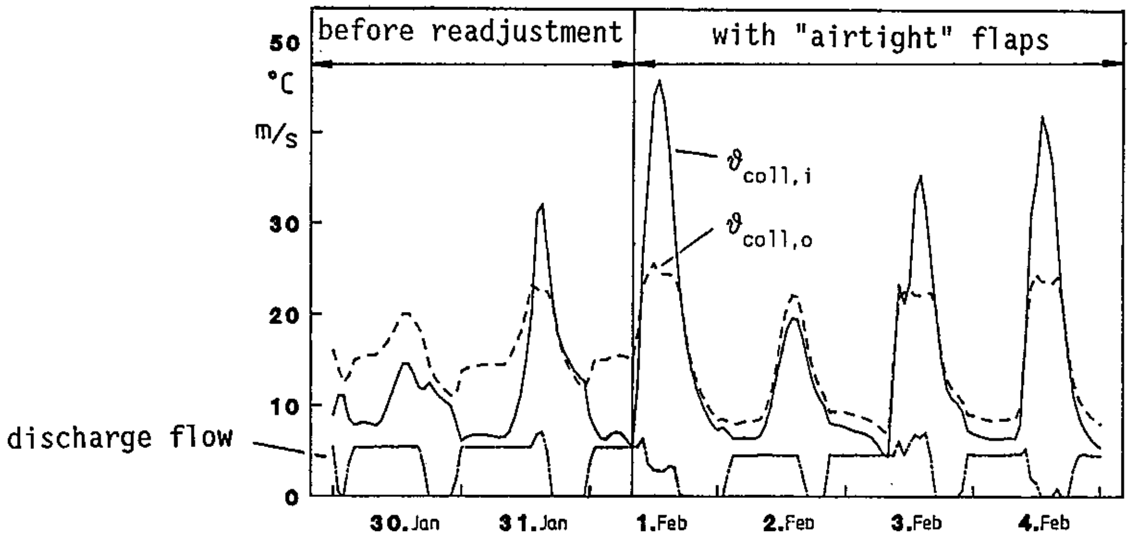
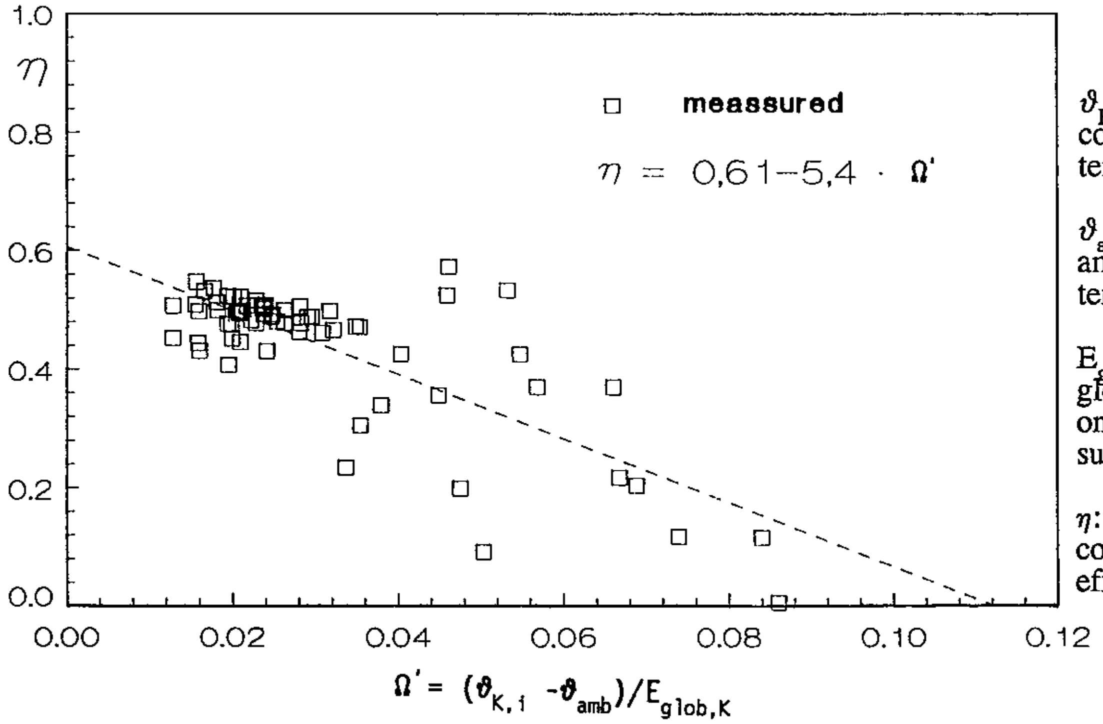


Fig.12: Temperature range at collector inlet and outlet before and after the readjustment

Figure 13 illustrates the recorded thermal behavior of the air collector of Schopfloch Kindergarten. The thermal efficiency η_0 - provided there are no thermal losses which is ($\vartheta_{collector} = \vartheta_{ambient}$) - is the result of the optical losses, determined by the $\tau\alpha$-value, and the collector efficiency rate F_R.

Measurements of the covers' transmission showed a reduction by 10% to $\tau = 0.79$, which is caused by aging and pollution. The recorded value of $\eta_0 = 0.61$ can be explained by the bad transfer of heat from air to absorber sheet resulting in a collector efficiency rate of $F_R = 0.79$. A linear polynominal regression for the values leads to an overall heat loss coefficient $U_{eff} = 6.8$ W/m^{2}K. This rather high value for double covers is the result of a strong dilation of the outer foil causing it to rest on the inner one so that large areas of the collector have practically only a single cover. This shows that foils are not useful for outer covers of collectors or that at least there should be tightening mechanisms. A comparision between heat gained by the collector and the radiation during operation results in a mean efficiency of 32%.



$\vartheta_{K,i}$: collector inlet temperature

$\vartheta_{amb.}$: ambient temperature

$E_{glob,K}$: global radiation on collector surface

η: collector efficiency

Fig.13: Efficiency curve of the collector

The high absorber temperatures reached during during summer time when the solar system is switched off, disolved the adhesive that glued the absorber foil to the underconstruction. Back in active use the underpressure in the collector causes a blowup of the foil that brings it into contact with the cover foils. This leads to additional losses and a pressure drop in the collector.

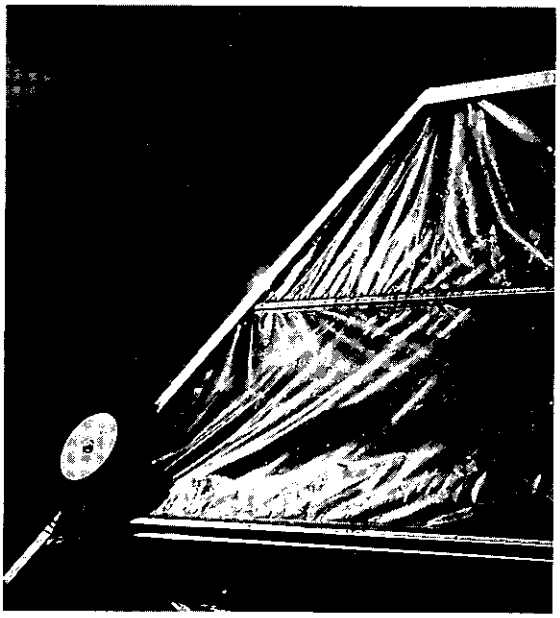


Fig.14: Cover details

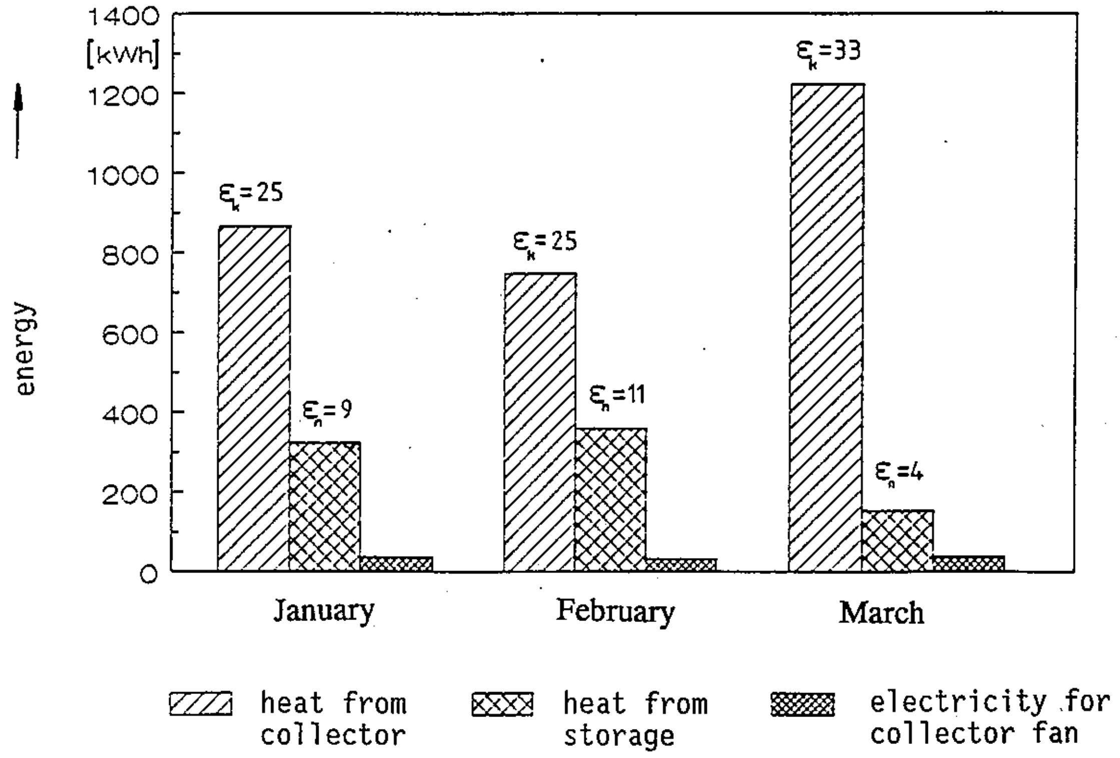


Fig.15: Comparision of the heat gained through the collector, discharged from the storage and the electricity used for the process

Figure 15 shows the current consumed by the collector and the heat gained and transfered to the storage as well as the heat discharged from the storage and used by the heating system. The heat delivered to the storage and the current consumed by the collector fan show that during each of the 3 months approx. 0.04 kWh current were needed to gain 1 kWh heat from the collector. This means a power coefficient of $\epsilon_K = 25$. The power coefficient ϵ_H however, discribing the correlation between current consumption and discharged heat is in the range of 11 to 4. Whereas the fraction of heat used for the operation of the collector fan was about 10% of the heat consumption in January and February, the analysis showed a value 2.5 times higher in March. This large difference was due to an error in the control device. Between March 6 and March 19 no energy was discharged from the storage although a great amount of heat was charged into it.

Measurements at the rockbed storage

Despite the low total height - the kindergarten is a single-storey building with no cellar - a long storage is provided by the storage's U-form. The starting point for the collector operation is determined by a comparision between the actual storage temperature and the collector temperature. At a difference of 8 K the collector fan is activated and at a difference smaller than 3 K it is shut off. The storage was sized after the rule of thumb that gives a factor of 0,5 of the collector area. This means a 20 m^3 rockbed storage with a porosity of 40%. The storage walls are made of 10 cm concrete which is insulated with 10 cm Styropor^R. Results show that the capacity of the surrounding walls is not negligible and is in the range of 50% of that of the storage material.

Figure 16 illustrates the solar system's loading operation during which the flaps on the heating system side should be closed completely thus forcing the hot air from the collector to follow the U-form of the rock-bed. Through the distribution of the air in the space above the rock-bed the whole surface area of the storage's upper warm part has the same temperature. The high measured temperature gradient between the storage layers illustrates the fact that the heat transfer from air to rock takes place on a very short distance (compare fig.17). Beside the pure loading operation direct heating with the hot air from the collector is possible through bypassing the storage.

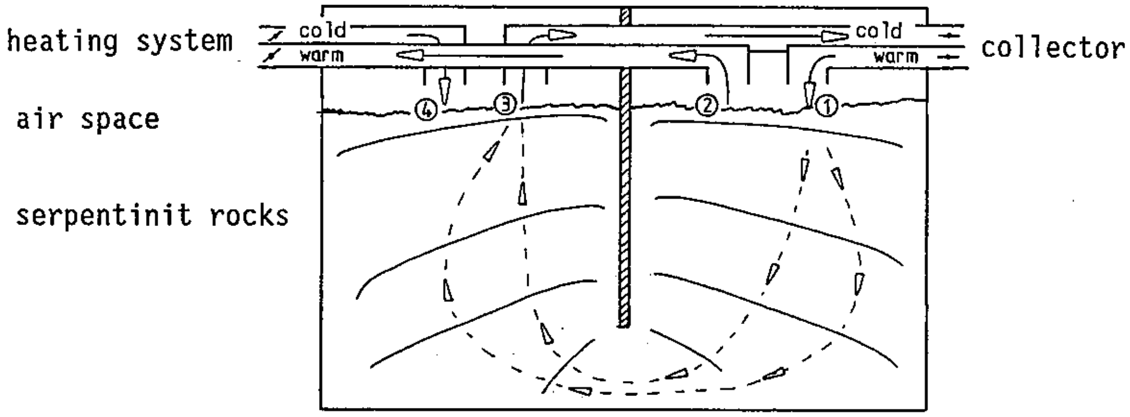


Fig.16: Loading of the storage

A typical temporal temperature curve on storage loading is given in fig.17. The examined four days were high in solar radiation. The flow velocity at the storage outlet shows that there was no active discharging during this period (the Easter holidays).

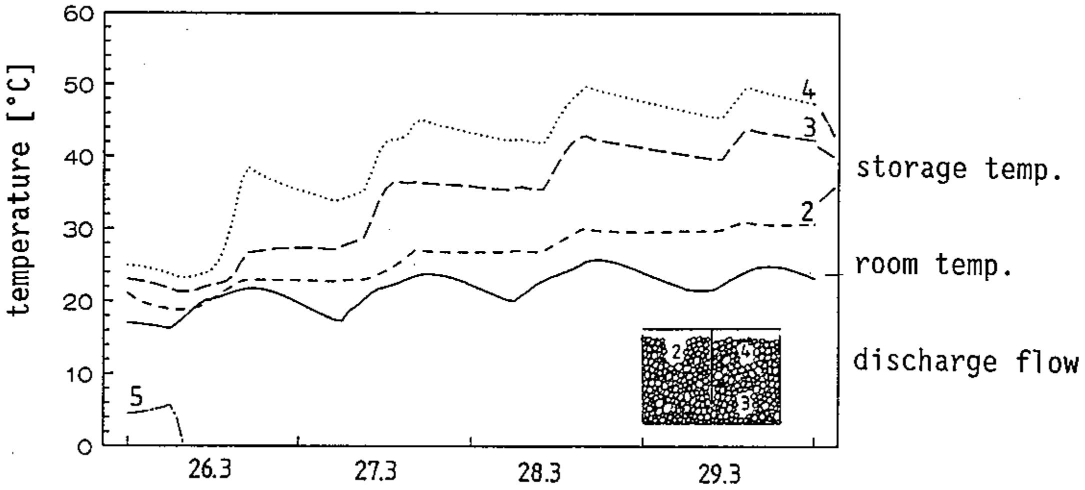


Fig.17: Thermal distribution at loading and passive discharge

As fig.15 shows the storage efficiency for active discharge was 50% after the collector flaps were filled in February. A great part of the storage heat losses to the surrounding is to the benefit of the building. From material data the storage's capacity value had been calculated at 6.1 kWh/K. It was then compared to the measured value of 11.3 kWh/K recorded during the charging period in fig.17. The difference between the two values is caused by the thermal capacity of the steel-concrete construction of the storage with a thermal capacity of 3.6 kWh/K which adds up to roughly the measured value.

Measurements at the heating system

The heating demands per Kelvin temperature difference of the kindergarten depending on the daily amount of global radiation is illustrated in fig.18. The gas boiler's measured efficiency of 6.5 kWh/m^3 is included. With increasing radiation the heat demand decreases by the active and passive gains.

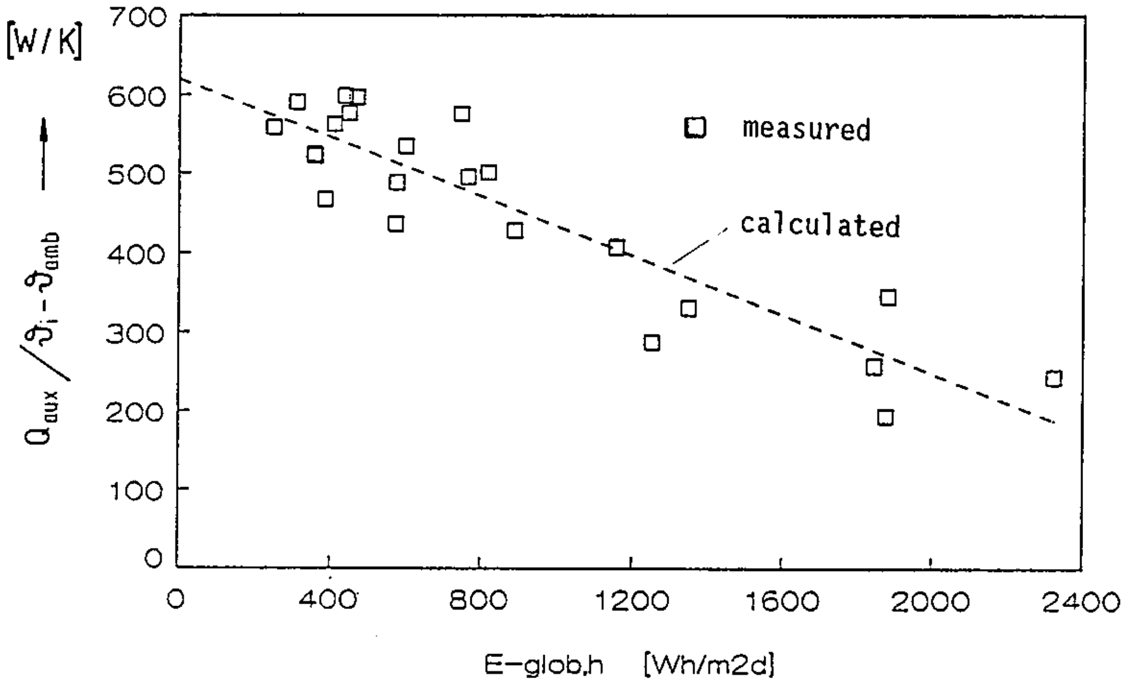


Fig.18: Building heat consumption per Kelvin temperature difference depending on the daily solar radiation

Regression analysis results in a specific thermal value of 615 W/K for transmission and infiltration, which is near the design value of 645 W/K. This actually high value can be lowered by installing temporary insulations, because 45% or 216 W/K fall to the window fronts. Using the thermal value and the building's nightly cooling rate its thermal capacity was determined at C_{build} = 27 kWh/K. The rock-bed storage, which can be considered separately, has a heat capacity of 11.3 kWh/K. The comparision (in Table 1) of the thermal energy - auxiliary and solar - and the energy used to distribute the heat in the building shows a fraction of 20 to 25% over the months. This fraction is very high and it makes clear that a stage operation for the heating fan should be installed.

Table 1: Energy consumption for two heating periods

	Degreedays [DD]	Q_{gas} [kWh]	$Q_{el,tot}$ [kWh]	$Q_{el,dist.}$ [kWh]	$Q_{el,col}$ [kWh]	$Q_{act,col}$ [kWh]	Q_{sto} [kWh]
88/89	2881	20 506	6 734	4 317	187	4 640	834
89/90	2912	22 570	4 605	2 230	220		

The composition of the kindergarten's current consumption is illustrated in fig.19. In the 6 months between November '88 and April '89 the overall current consumption was approx. 6500 kWh. Compared to the heating fan with a mean value of 63% the collector fan consumes only 2.6% of the total current consumption. Control devices and the data logger have a fixed value of 8.6 kWh/day or 24%. Lighting and other users such as refrigerators and stoves consumed meanly 10%.

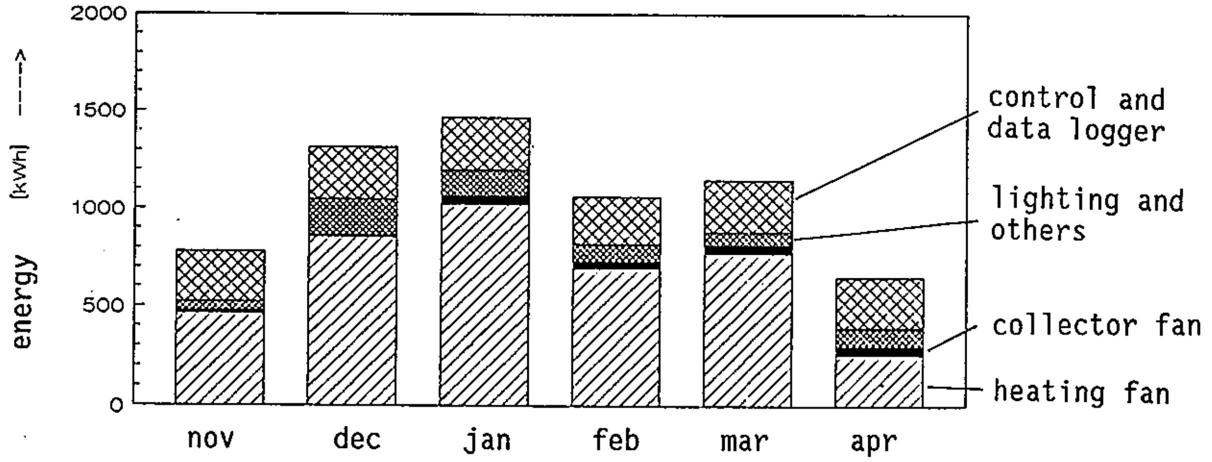


Fig.19: Distribution of the current consumption on the various users

A division of the various sources of heat and their representation in monthly sum values can be seen in fig.20. The solar system's fraction (active and passive provisions) for the whole heating period between October '88 and April '89 was:

$$f_{solar} = Q_{solar} / Q_{heatload} = 15298 \text{ kWh} / 42537 \text{ kWh} = 0.36$$

This means a specific heat load of 169 kWh/m2 applied to the heating space and an auxiliary heat demand of 109 kWh/m2 in bought energy. For January to March the solar fraction was split up into the active solar heat to the storage and the remaining amount, the passive contribution. The low values in March were caused by a control error.

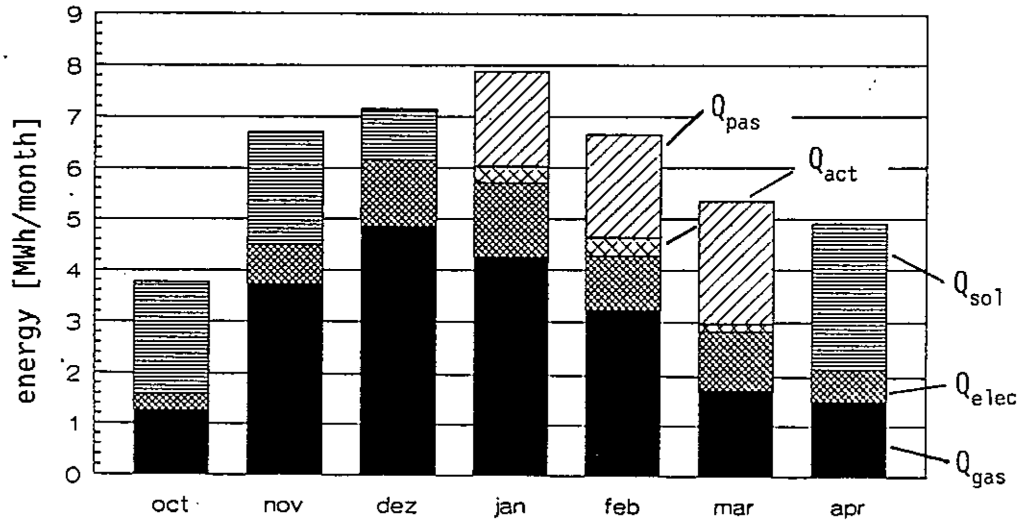


Fig.20: Composition of the energy consumption covering the heating demand

Passive system

The recorded passive gains represent the heat gains through the window fronts to the east, south and west which helped cover the heating demand. Since there was no overheating of the rooms in January and February an utilization of 100% can be supposed for this period. A comparision of the solar gains - 23.4 kWh/m^2 - and the heat losses - 32.5 kWh/m^2 -of the window area leads to a netto loss value of 9.1 kWh/m^2. This value corresponds to an effective heat loss coefficient of 0.84 W/m^{2}K for the month of February.

Passive behavior of the building

With glazing areas of 70% to the east and 61% to the south the Schopfloch Kindergarten was designed for a high use of passive solar energy by direct heating. In fig.21 the gymnastic hall was used to provide an example of the passive behavior. With May 16 a particularly warm and radiation intensive day was picked for the graph. Therefore the temperature curves represent an extreme case. Since there was no heating during this period the temperature curves stem only from the passive behavior.

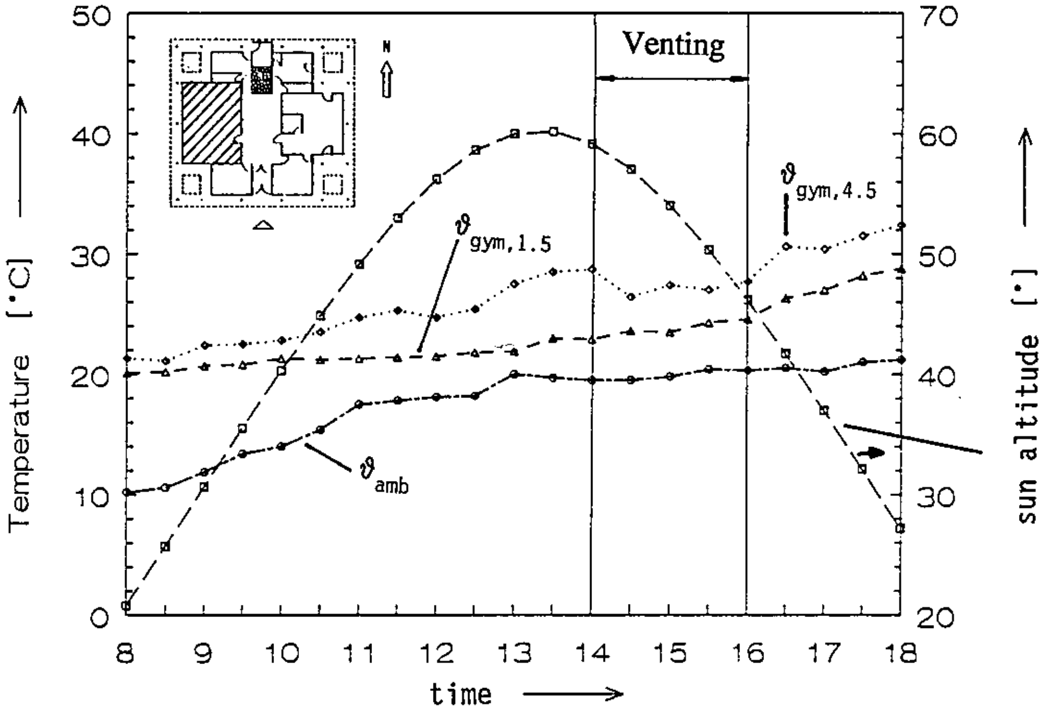


Fig.21: Temperature curves and sun altitude for the gymnastic hall aligned to the west on May 16

The room temperatures were recorded every 30 minutes at two heights. The graph shows a rise in temperature at 4.5 m height starting at 10 a.m. caused by the operation of the collector. After 1 p.m. a distinct rise in temperatures can be recorded for now the sun falls on the hall windows. The drop in temperture at 4.5 m height after 2 p.m. is caused by the manually controlled venting system in the shed roof. At 1.5 m height only a smaller increase can be observed as a reaction to the venting. After 4 p.m. with the stop of the venting - the kindergarten is now unoccupied - the temperatures rise to 29 and 32 °C at the various heights. Figure 23 shows the direct radiation coming through the windows on the hall's west side. These results make it clear that the shading through the roof overhang does not work for the gymnastic hall during this time of the year. Figure 22 shows the shading of the overhang for different orientations and months.

In addition to fig.21, fig.24 provides the temporal temperature curves for both group rooms, the atrium and the gymnastic hall on May 16. The large drop in temperature in both group rooms - quickly heated in the morning by the sun - is caused by windows and doors being opened. It can clearly be seen that in the evening there are no further rises in temperature in the rooms that are averted from the sun.

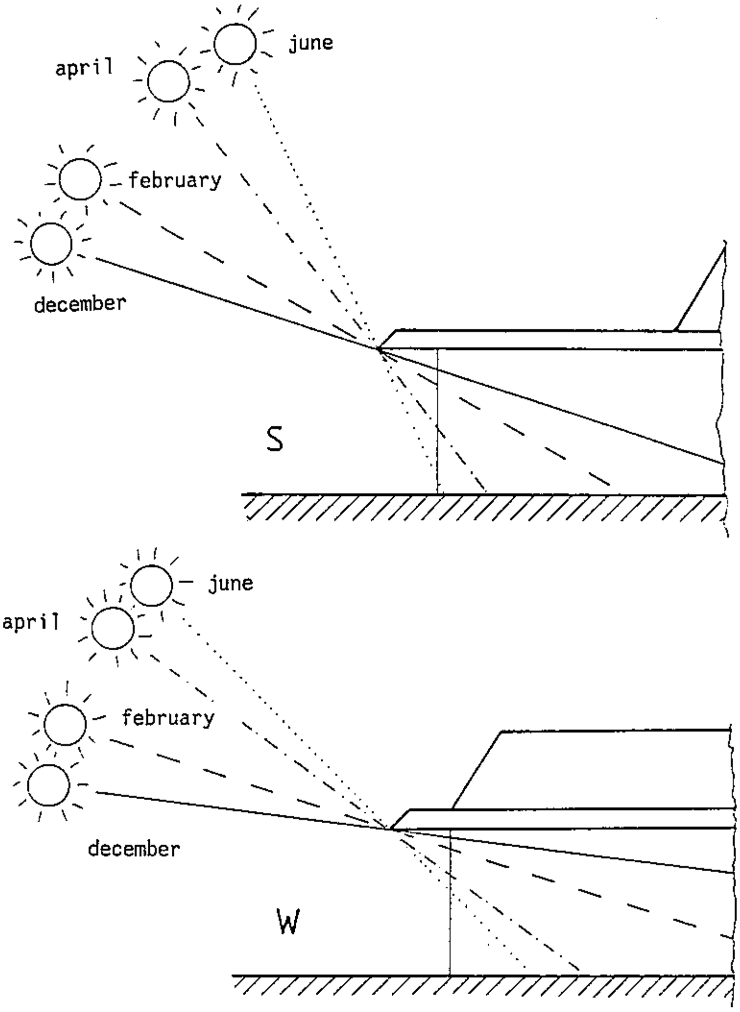


Fig.22: Shading by the roof overhang for the south and west orientations

Fig.23: Direct radiation into the gymnastic hall at 6 p.m.

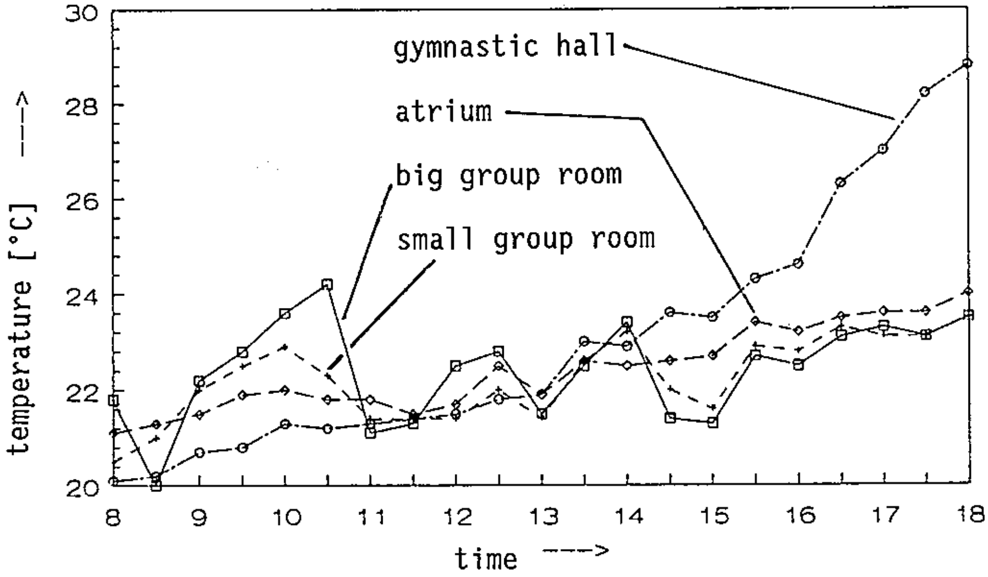


Fig.24: Temperature curves for group rooms, atrium and gymnastic hall on May 16

SIMULATION

Goals

Simualtion of the system under consideration was used to examine:
- sensitivity studies of various system parameter
- behavior of the system in the climates of Oslo, Copenhagen, Brussels, Zurich and Rome respectively

Simulationprogram

The SIMUL program was used for the simulation calculations. This program was developed at the Institute of Thermodynamics and Heat Transfer at Stuttgart University and is suited to model solar asssisted air heating systems. It examines various collector and system configurations using an hourly timestep. The building's heating profile is determined by a single zone model called HAUS. The following chart shows the setup of the program package.

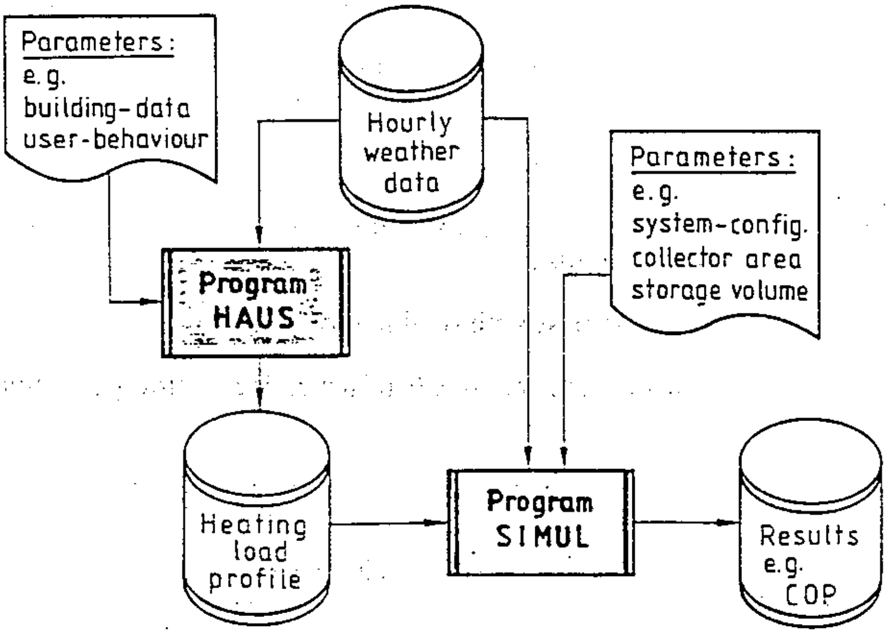


Fig.25: Flow chart of the simulation with SIMUL and HAUS

Model

Distribution of zones:	The building was represented by a single zone		
Layers of the walls:	The outer walls consist of: 10 mm wood 10 mm air gap 100 mm insulation 13 mm wood		

The mean heat transfer coefficient was determined at 0.445 W/m^{2}K

Internal load:	measurement results serve as input, excluding the heat gain caused by the occupants		
Air change rate:	Daily profile	8 a.m.- 5 p.m. 5 p.m.- 8 a.m.	0.7 1/h 0.2 1/h
Setpoint heating:	Daily profile	8 a.m.- 5 p.m. 5 p.m.- 8 a.m.	19.5 °C 17.0 °C
Weekly profile:	Monday - Friday Saturday - Sunday	occupied unoccupied	
Climate data:	Measured values		
System configuration:	Closed loop without mass flow control, rock-bed storage		
Collector:	Typ 1, one-pass with double covering		
Validation:	Against lab measurements of air collector storage system		

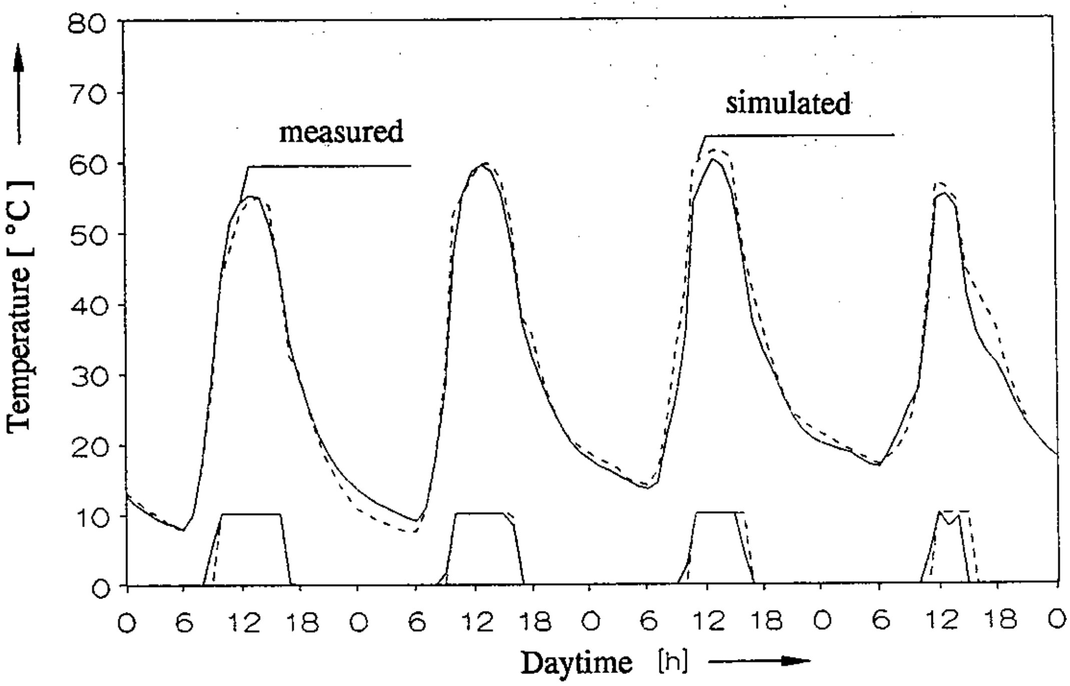


Fig.26: Collector temperatures measured and calculated

Parametric studies

For the example of the Schopfloch Kindergarten the following parametric studies have been done with the program SIMUL, a simulation program for solar assisted HVAC-systems.

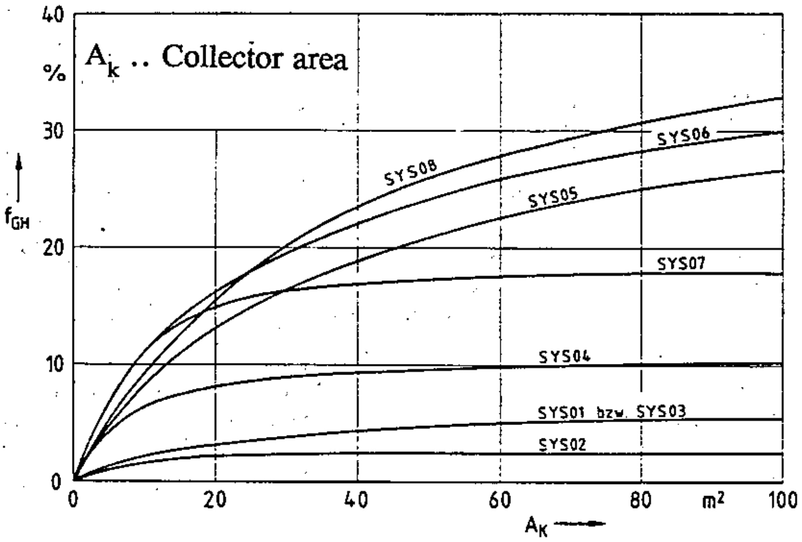
Table 2: The reference data

Systemtype	closed loop with rockbed storage
Collector area	38 m^2
Storage volume	20 m^3
Storage capacity	40 MJ/K
Collector/storage ratio	1.9
Collector slope	60 degree
Collector orientation	south ($\phi=0$)
Volume flow through the collector	44 kg/h m^2 = 35 m^3/h m^2
Collector construction	one pass, double glazed
Aspect ratio (l_k/b_k)	9.5
Duct length (non-insulated)	10 m
Heated area	250 m^2

System configurations

Table 3: System configurations

System-	Collector field		Mass flow	Storage type		add. hot water
name	opened	closed	control	water	rock	system
SYS01	x	-	x	-	-	-
SYS02	x	-	-	-	-	-
SYS03	-	x	x	-	-	-
SYS04	-	x	x	-	-	x
SYS05	-	x	x	-	x	-
SYS06	-	x	x	-	x	x
SYS07	-	x	x	x	-	x
SYS08	-	x	-	-	x	x



Definition:

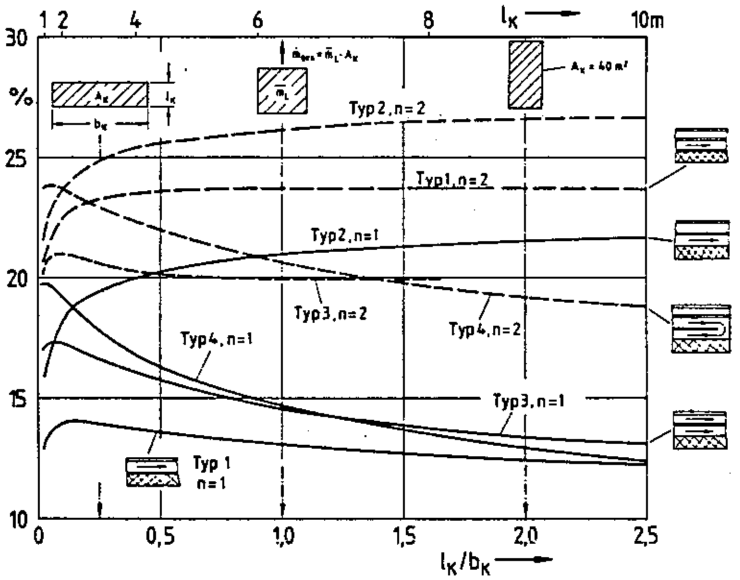
$$f_{GH}=\frac{Q_{sol,act}}{Q_{heating}}$$

Fig.27: Effect of the system configuration on the solar fraction (f_{GH}) according to the table above

Figure 27 shows that without a storage the solar fraction of an air collector system cannot exceed 10% of the heating demand. Using storage systems the ratio increases with the collector area. Rockbed storages are better than water storages because of the limited heat transfer between air and water in the real heat exchanger.

Collector construction

The following collector constructions differ in the way the air flows through the collector. Type 1 and type 2 are one pass designs, the air passing in front or behind the absorber. Type 3 and type 4 are two pass designs, with a parallel air flow in front and behind the absorber (type 3) or with preheating near the cover and a final heatup in the absorber. The ratio between the length l_K of the collector and the width b_K is an important parameter for air collectors. Double glazing is necessary for air collectors because the hot air is in direct contact with the inner cover.



one pass flow

two pass flow

Fig.28: Effect of the collector construction (type), number of covers (n) and the field geometry (l_K/b_K) on the solar fraction (f_{GH})

Orientation of the collectors

The optimal orientation of the collector area is facing south with a slope close to the value of the geographical latitude. Steeper slopes around 60° are optimal for the winter period, when the heat demand reaches its maximum.

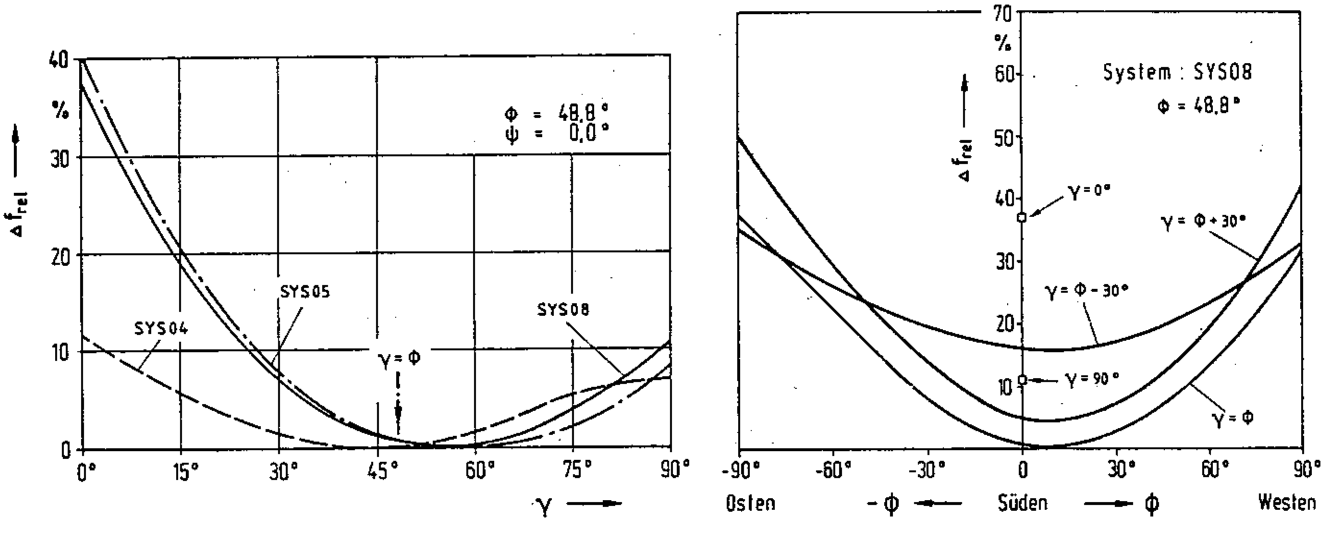


Fig.29: The relative decrease of the solar fraction (Δf_{rel}) depending on the collector slope (γ) and the orientation (ϕ) of the collector field

Collector area/Storage volume ratio

Figure 30 describes the effect the heat capacity of a pebble-bed storage has on the solar fraction for differently sized collector areas. The storage capacity was varied up to 60 MJ/K. This corresponds to a storage volume of approximately 48 m^3 with a density for rock ρ_{St}= 2.6 kg/dm^3; a heat capacity for rock c_{St}= 0.835 KJ/(kg K) and χ_{Sp}= 0.43 for the ratio of rock to the storage volume.

$$C_{Sp,St} = \rho_{St}\, c_{St}\, (1-\chi_{Sp})\, V_{Sp,St}$$

For these anlysis the storage was designed as a cube. For a given collector area the solar fraction at first increases with the storage capacity and then remains approximately constant with $C_{Sp,St}$ in the region analysed here. From the results presented in fig.30, an empirical equation for the dimension of a pebble-bed storage can be given as:

$$\text{storage capacity} = \text{collector area} * C_2$$
$$C_{Sp,St} = A_k * C_2$$

with $C_2 \approx$ 0.24 - 0.28 MJ/(K m^2)

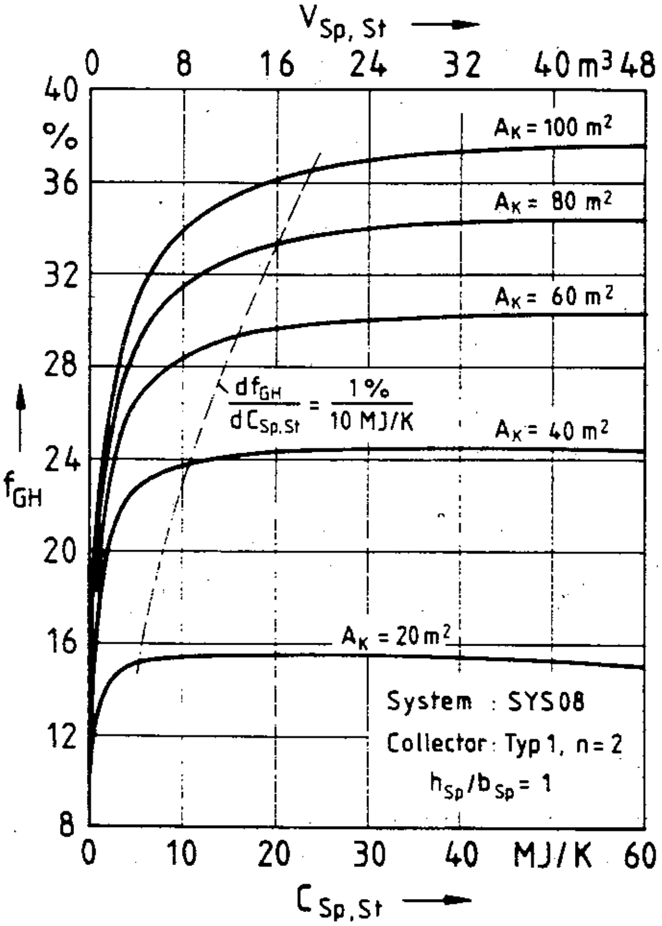


Fig.30: Effect of the thermal capacity of a rock-bed storage ($C_{Sp,St}$) on the solar fraction (f_{GH}) of different collector areas (A_K)

Air speed through the collector

It can clearly be seen that longer collector fields (larger l_K/b_K) result in larger solar fractions. Besides fig.31 indicates that with an increase in area and lenght (l_K/b_K) of the collector field a smaller mass flow rate should be chosen. For an area of e.g. 40 m^2 and an aspect ratio of 0.05 - this corresponds to l_K= 1.4 m and b_K= 28 m - an optimal air flow rate is obtained at approximately 35 kg/(h m^2). For the same collector area and an aspect ratio of 2.5 (l_K= 10 m, b_K= 4 m) an air flow rate of only 25 kg/(h m^2) has to be chosen.

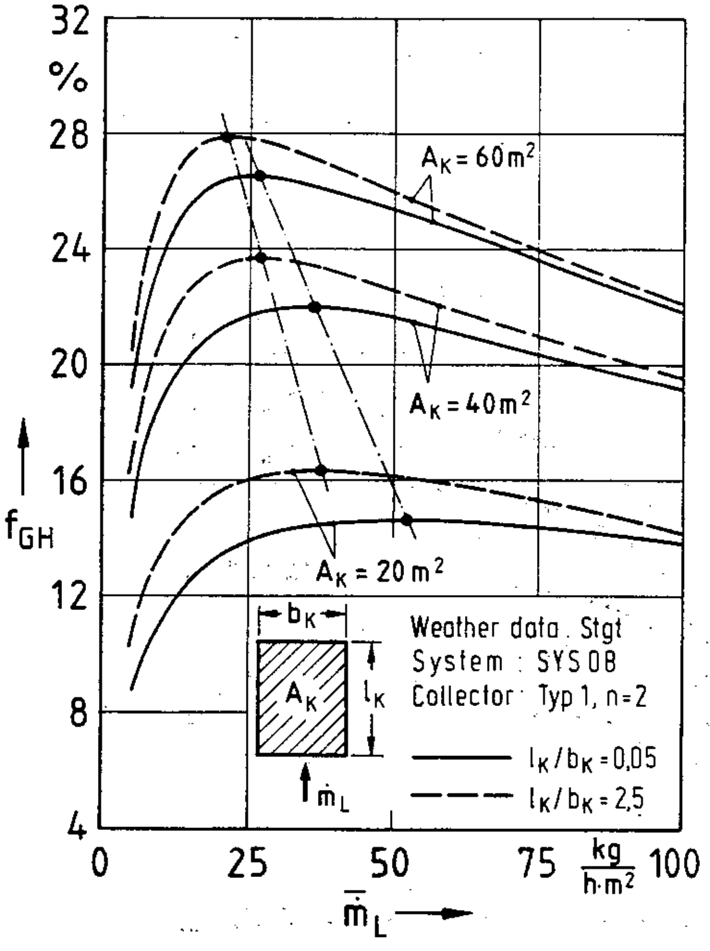


Fig.31: Solar fraction and mass flow rate

Figure 31 presents the solar fraction versus the mass flow rate (m_k) based on the collector area; various areas with different aspect ratios (l_K/b_K) are given as parameters.

Duct lenght and insulation

Figure 32 shows that the heat capacity of ducts is of minor importance in regard to the thermal insulation of the ducts. The influence of the thermal insulation rises correspondingly to duct lenght. The figure also illustrates that a thicker thermal insulation layer results in a smaller increase of the solar fraction ; e.g. for l_P= 20 m and C_P= 4000 J/(K m), the solar fraction increases from 16.5 % for the non-insulated duct to 22 % for a layer thickness of 2.5 cm; a doubling of the thermal insulation layer to 5 cm results merely in an increase of absolute 1% in the solar fraction.

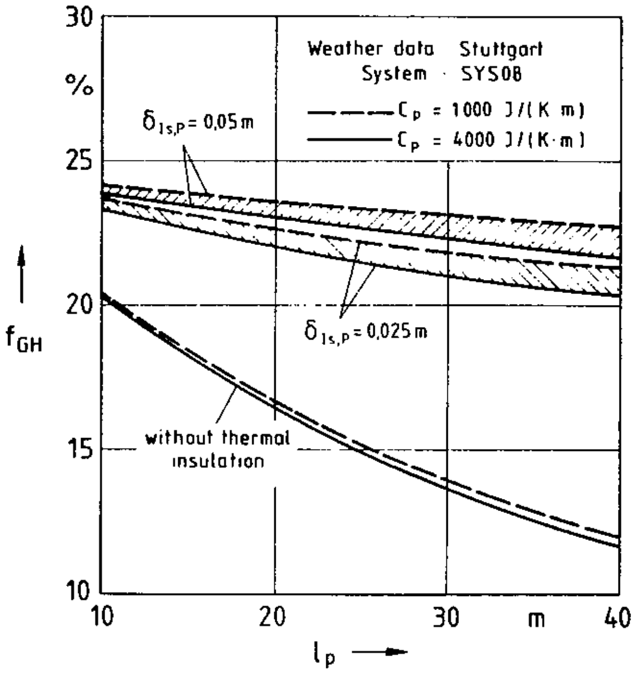


Fig.32: Solar fraction as a function of the duct lenght (l_p), different thermal insulation thickness ($\delta_{Is,P}$) and heat capacity (C_p) of the air duct

Effect of meteorological data

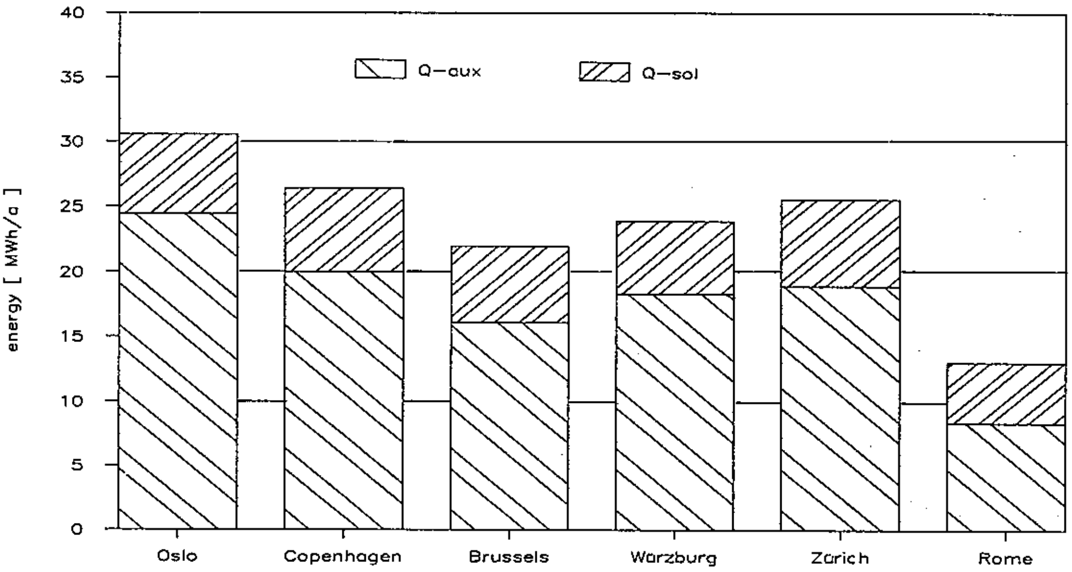


Fig.33: Influence of the climate on the heating load and the solar input of the air-heated kindergarten.

For this analysis the building was considered in the context of existing reference data for the 6 different European climates. Figure 33 shows the auxiliary heating load with and without the air collector system defining the difference as the solar gains. System and building were considered in different climates without adapting the sizing to the respective climates.

SUMMARY

Interpretation of measurements and parameter studies lead to the following conclusions and suggestions:

- the system works, yet its thermal efficiency still needs improvement to reduce the auxiliary heating consumption of 106 kWh/m^2

Therefore:

- temporary insulations against heat losses should be installed at the large glazing surfaces which could be used as shading devices too
- the actual room temperature should be included as a control value in the heating control
- the gas boiler should be included in the control cycle to reach an efficiency over 65%
- the heating fan should operate in stages to save electricity
- ventilation flaps in the collector and storage cycle should have felt bonds to be airtight
- there should be the possibility of regulating the two heating zones separately

Conclusions drawn from the example under consideration:

- foils without tension regulators are unsuitable for the outer covering of collectors
- a twopath airflow around the absorber results in a higher collector efficieny
- choice of material and construction (absorber and its fixing) have to consider temperatures of up to 100 °C in the collector.
- airtight airflaps have to be used
- up to 25% auxiliary energy is needed for the distribution of heat in the air heating system
- for 1 kWh heat the collector cycle needs 0.04 kWh electricity for the fan
- collector ducts should be insulated
- storage capacity is increased by factor 1.9 by using enclosing walls

REFERENCES

Schuler,Matthias "Basic case study Schopfloch Kindergarten" IEA-Task XI, Institut für Thermodynamik und Wärmetechnik, Universität Stuttgart

Schuler,M., Laubscher,H.-P. "Messungen am solarunterstützten Heizungsystem im Kindergarten Ezach" Institut für Thermodynamik und Wärmetechnik, Universität Stuttgart

ENTE BUILDING

Direct Gain

Report prepared by
Matthias Schuler
Institut für Thermodynamik und Wärmetechnik
Universität Stuttgart
1990

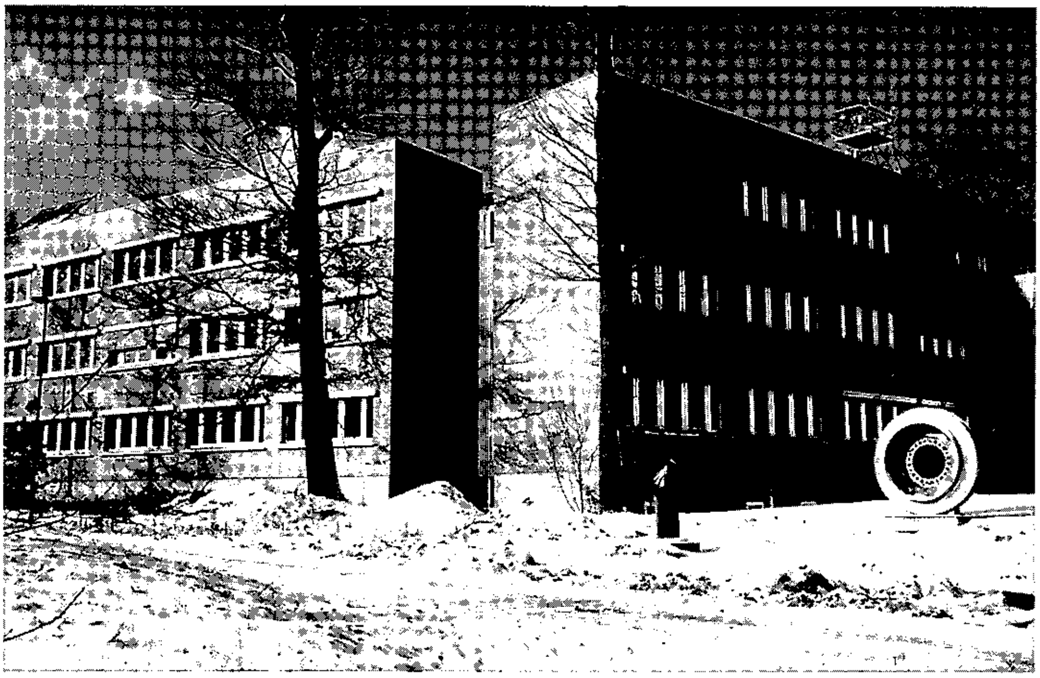


Fig.1: A view of the ENTE-building from the south-east

ABSTRACT

The "Energietechnik" institute's building at Stuttgart University was designed as an office and laboratory building. It is well insulated and the offices and laboratories which are provided with large windows are located in the eastern and southern parts of the building. On the northern and western front of the building there are only very small windows. The shed-type roofs of the two institute halls are aligned in east-west direction. Their southern slopes are mounted with unglazed active collectors. In summer the absorbers deliver heat to a seasonal storage of 1000 m^3 volume, which is an artificial aquifer. Throughout the heating season this storage is discharged by a heat pump to heat the building's office space. Due to passive heat gains and a high level of insulation the building has a low heat demand (68 kWh/m^2 a), 66 % of which can be covered by heat from the storage. The occupants appreciate the bright offices and corridors. Nearly all offices are orientated to the East, causing a good daylighting without the problems of overheating by solar gains.

The measurements of two seperate offices shows a solar contribution of the annual heating demand for the east orientated module in the range of 25%. In the air conditioned south orientated office only 10% of the solar gains are usable while the rest together with the fan power increase the cooling load.

INTRODUCTION

The architect M.Nülle was asked to design a building with a low heat demand as well as an optimal use of daylight in the working-rooms. The space heating system was set up as a low temperature heating system. The building was chosen by the TASK XI group in order to have a reference case of a standard office building, which could be monitored in detail. To exclude the user profile's influence one unoccupied office with an air conditioning system was monitored seperately. This makes it much easier to compare the measurements to simulation results without having to calibrate the model.

Measurements of two heating periods have been done since 1986. The aims of the reference case study were

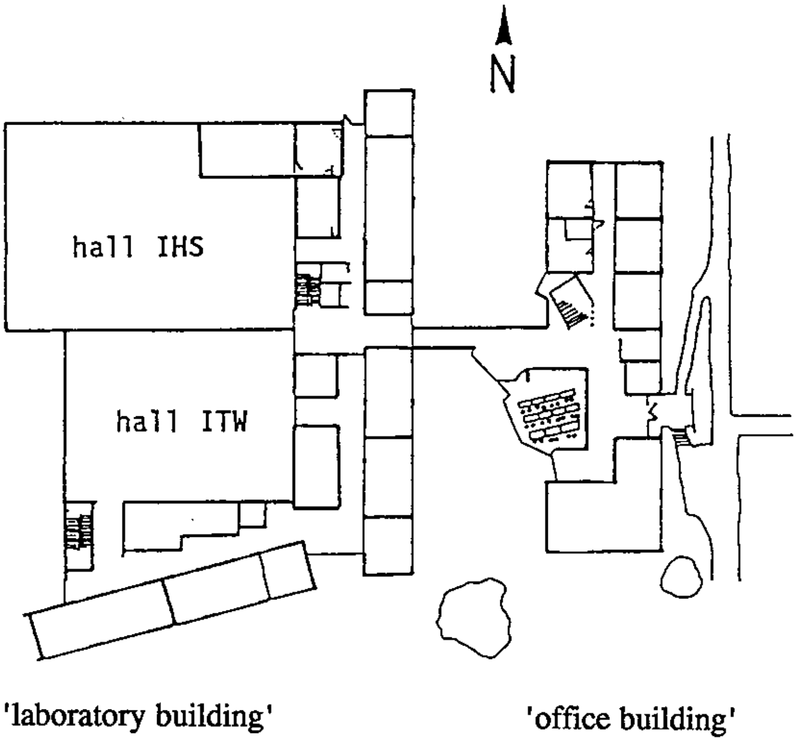
- to test the efficiency and the utilization of direct gains in an office building
- to examine the influence of a very massive building on the annual heat demand
- to compare heating and cooling demands

BUILDING DESCRIPTION

Location

The building is located in Stuttgart-Vaihingen on the campus of Stuttgart University. To the south, east and west sides the building stands detached without shadows. On the north side a small group of trees seperates the building from a large parking lot.

Form



Surface areas:	[m^2]
Ground floor	2 650
Roof	2 698
Wall (excl. windows)	2 220
Windows	600
Heated areas:	[m^2]
whole building	4 850
office building	1 375

Fig.2: Floor plan of the office and laboratory building

Figure 2 shows that the whole building is divided into two parts. The two-storey office building is connected to the three-storey laboratory building by a corridor. The main orientation of the two parts of the building is east and south, with the erecting bays as buffers to the north and west. The rest rooms and the staircases separate the two parts of the building.

Function

The institutes occupying the building - with approx. 50 employees - do research in the field of active and passive solar systems and hydraulic jet engines. There are also two lecture halls for the institutes' teaching assignments in the building. The halls in the laboratory part of the building serve as erecting bays and laboratories for large projects. The flat roofs serve as test facilities for air and water collector systems. There is also a meteorological station which has collected hourly weather data since the date of occupancy.

Construction

The University buildings are reinforced skeleton structures with interior and exterior masonry walls. The exterior walls include rockwool insulation and an air gap of 4 cm (compare fig.3). The north and the west facade are covered with aluminum panels. The windows are double glazed and timber framed. The measured total heat loss coefficient of the building is 6 570 W/K.

Specific heat losses:	[W/m^{2}K]
Floor	0.44
Walls	0.34
Roof (average)	0.66
Windows and frames	3.00

Envelope heat losses:	[W/K]
Transmission: (design)	4 610
Infiltration: (conditions)	930
Measured all:	6 570

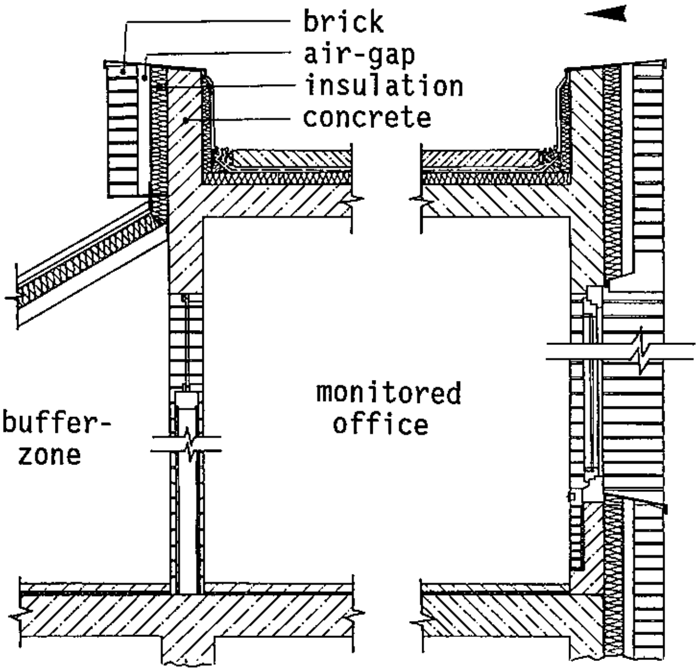


Fig.3: Construction details of a south-faced office

SOLAR FEATURES

Servives

The heat for the ENTE-building is supplied by the university's district heating system. The part of the building which contains the laboratories is furnished with a conventional heating system 70/50 °C. The space heating radiators are fitted to the low temperature heating system 50/40 °C in the building's office part. A heat pump delivers heat from the seasonal storage to that part of the building. Charged during the summer with the gains of 211 m^2 unglazed collectors, the storage-heat pump system covers 92 % of the heat demand. The rooms in the laboratory building, which are aligned to the south, are provided with air-conditioning to allow cooling in summer or during an experimental phase. The artifical lighting is manually operated but in the circulation areas - that is staircases and corridors - time switches have been installed. The installed capacity of the space heating is 44 W/m^2 heated area.

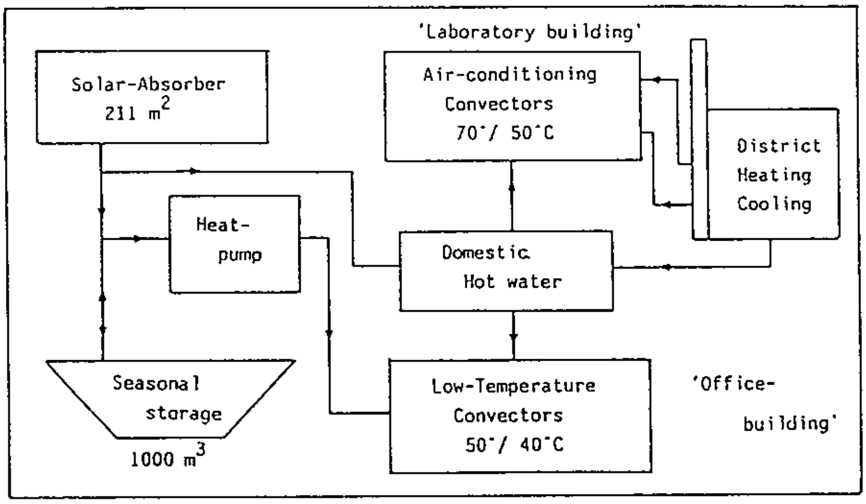


Fig.4: The office building's heating system

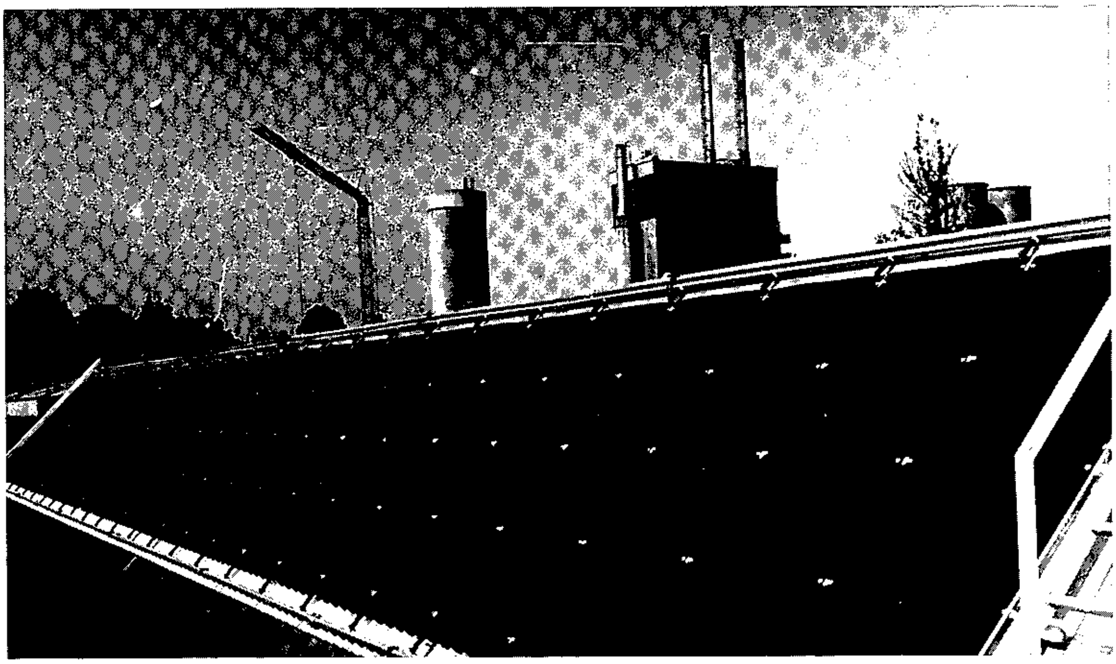


Fig.5: The unglazed absorbers on the southern shed roof

Passive systems

The large windows in the rooms provide a maximum of daylight but they also cause high undesirable seasonal heat gains and losses. To avoid overheating in summer it is possible to close external shading devices that are operated manually. On the north side of those rooms that were monitored in detail, a corridor acts as a buffer zone against the cold ambient air.

Glazing Properties:

Double glazing
U = 3.0 W/m^{2}K
Solar trans. = 85 %
Frame factor = 0.35

Window Data: [%]

Glazing factor = glazing/ exterior surface

east	23.1
south	22.6
north, west	0

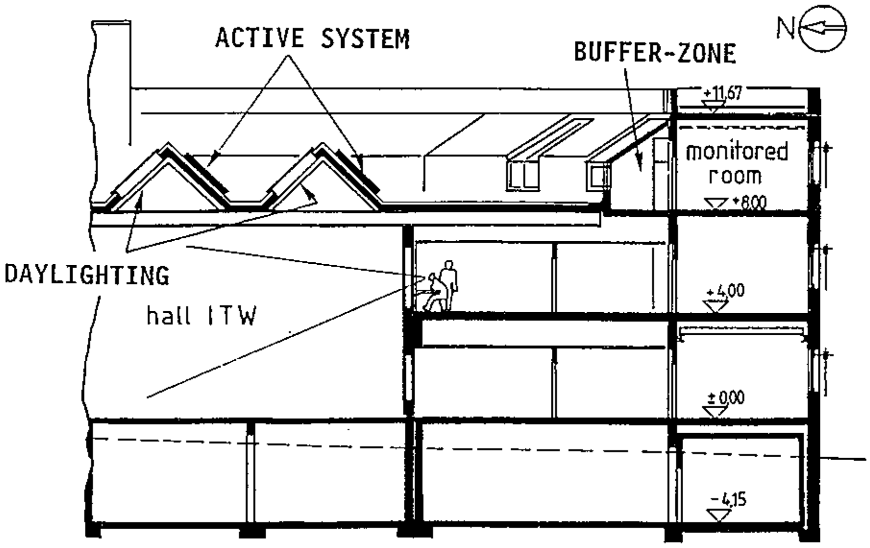


Fig.6: North/south cross-section of the laboratory building

System control

The temperature of the water circulating in the heating system is controlled by the ambient temperature. A night set back that had originally been installed in the system was switched off after the first heating period, because the high peak load in the morning could not be covered by the heat pump and the district heating had been activated. In the laboratories the shading devices are operated manually. The rooms have air-conditioning systems with heating and cooling coils and the set point of the room temperature can be chosen by the user.

MEASUREMENTS

Objectives / Methods

The overall aims of this study were:
- recording the heating, cooling and current requirements of the whole building and of its seperate parts
- testing the efficiency and the utilization of direct gains in an office building
- influence of the mirco-climate and the effect of long-wave radiation exchange

During the measurement period the following data was collected:

Climate:
- ambient air temperature and humidity
- wind speed and direction
- the horizontal, global and diffuse solar radiation
- sky temperature
- ambient air temperature at a distance of 10 cm from the southern wall

Building:
- energy consumption of the space heating measured seperately for the different systems
- energy use for domestic hot water, current consumption for lighting etc.
- temperatures in the corridors
- qualitative heat losses recorded with an infra-red camera

Monitored offices:
- air temperatures at different levels
- radiation temperature
- temperature of walls, floor and ceiling
- humidity
- the vertical global radiation in front of and behind the glazing
- pressure difference between indoors and outdoors
- surface temperature of the glazing indoors and outdoors
- infiltration and air-change rates
- energy consumption for space heating and cooling
- energy consumption for lighting
- temperature on the outdoor surface of the wall
- air temperature in the air gap on the vertical wall

Human factors:
- door and window contacts to control the opening times

Data map

For data logging a personal computer was connected to a 80 channel scanner and a 16 bit A/D converter. All channels were measured every minute and the hourly integrated values were stored in the intern hard disk. Using table calculation programs the results were then analysed. In addition to this the values of the heating, cooling and current consumption of the whole building were documented in monthly intervalls. The data of the seperate office building was recorded hourly.

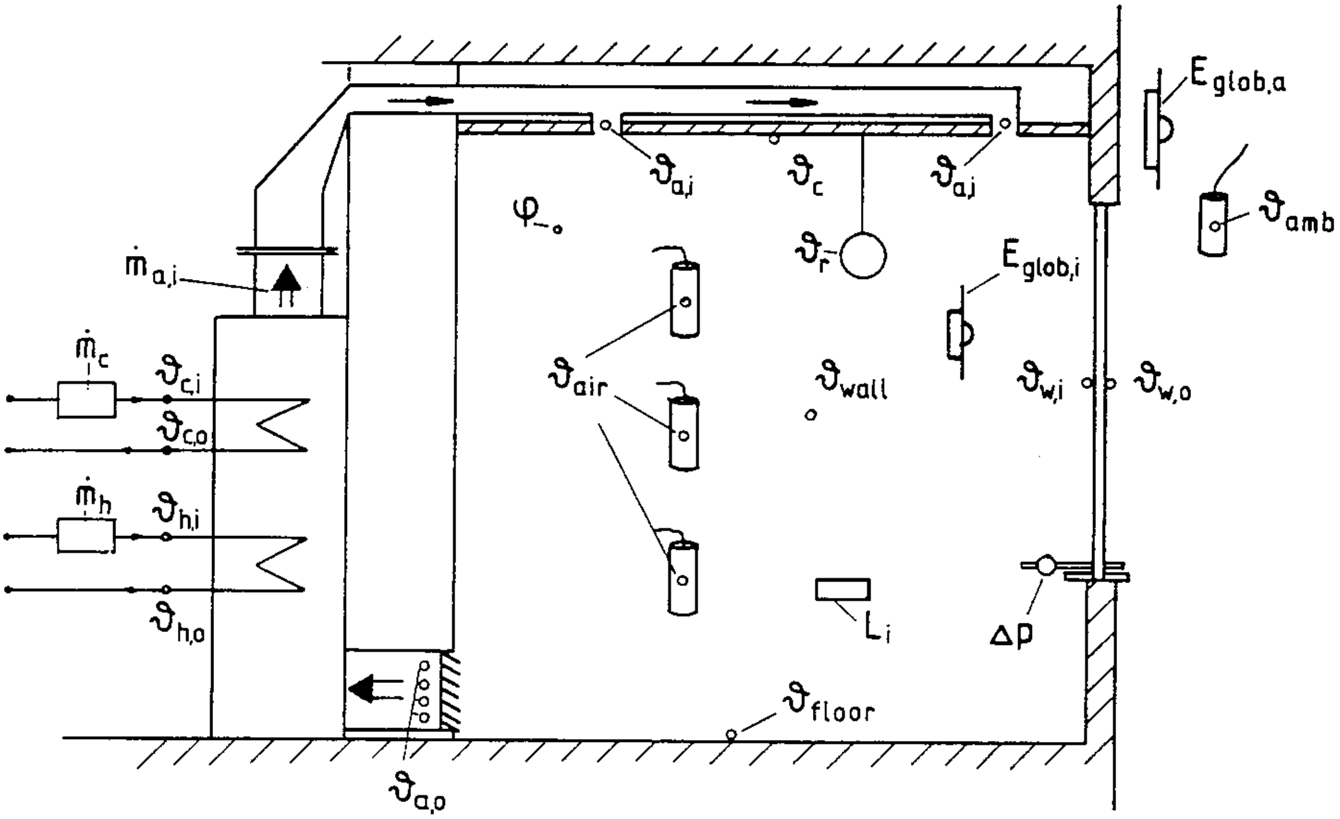
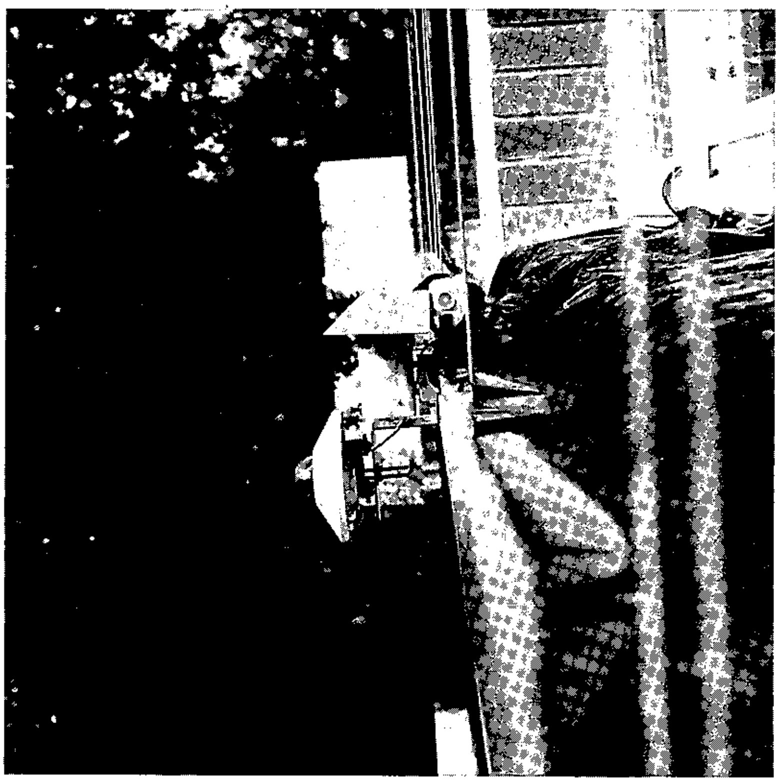


Fig.7: Measuring equipment in the monitored office

Two seperate offices were monitored in detail (compare fig.7). The temperatures were measured using Ni-CrNi thermocouples, calibrated in the institute's own calibration station. The air temperatures were measured with specially developed devices, which are double shaded against thermal radiation and artifically vented. To record direct gains in the room the solar global radiation was measured on the southern wall outdoors as well as indoors directly behind the glazing.

MEASUREMENT RESULTS

Micro climate



The climate data measured on the roof of the building and at the south front wall show a significant difference in ambient temperature. They are a good illustration of the micro climate prevailing close to the wall. For the facade the ambient temperatures have an influence on the outside heat transfer coefficient and on the heat losses through the walls.

Figure 9 shows the differences in ambient temperature and the global radiation on the vertical south recorded during a fair weather period in June 1988. The profiles show the expected relation between the air temperature and the radiation. This explains the higher peak in front of the wall. Interesting is the lower decrease during the afternoon and the constant difference during the whole night. This shows the influence of the storage effect and the radiative losses.

Fig.8: The vented air temperature sensor

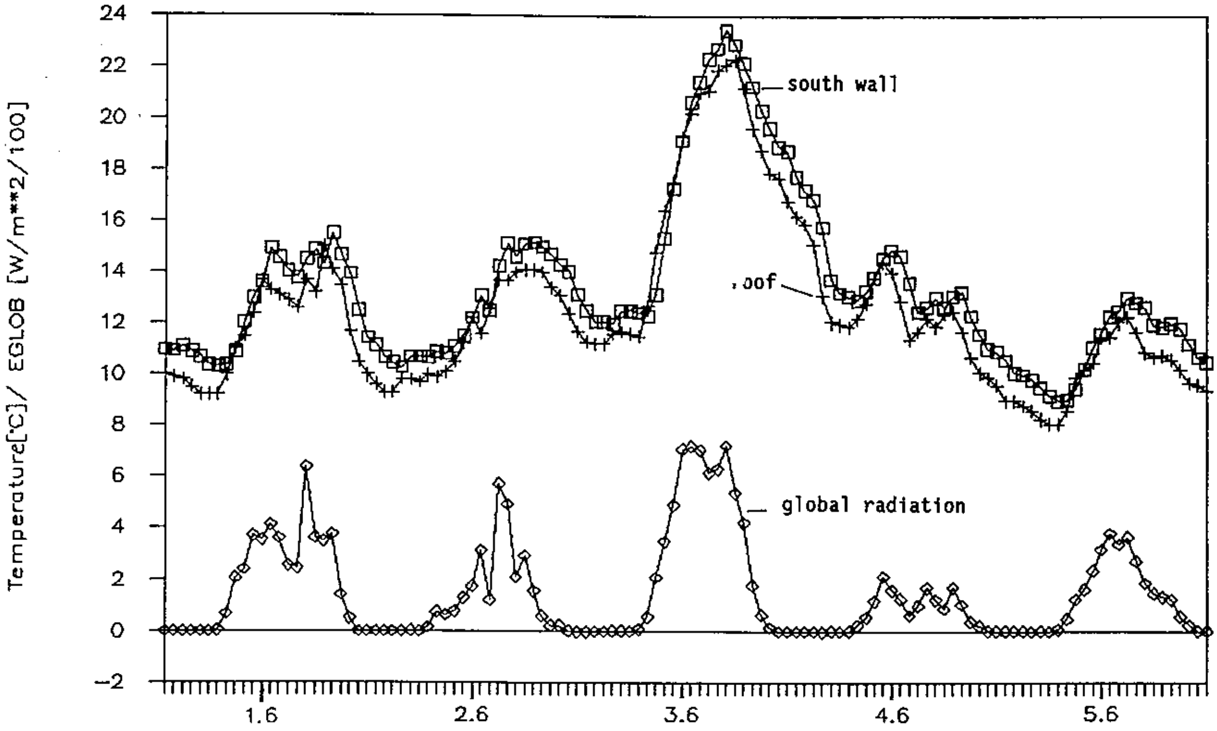


Fig.9: Ambient temperature measured on the roof and at a distance of 10 cm from the southern wall and the global radiation on the vertical south

The whole building

Figure 10 shows the monthly energy consumptions for heating, cooling and current in 1987. It is important to note that these figures include the high amount of energy consumed by the compressors that are used to cool seven climate-cells in the cellar of the building's laboratory part. The figure also includes the current consumption of the heat pump in the office heating system that amounts to 33 MWh over the year. In the laboratory part of the ENTE-building two computer rooms and twelve laboratory rooms are furnished with air-conditioning systems. These systems are connected to the heating and cooling water distribution system. The annual cooling consumption for 1987 was 453 MWh. The university had to pay 65,530 DM for the cooling consumption of 1987, which corresponds to 140 DM/MWh. The district heat has a price of 100 DM/MWh. In table 1 the different consumptions are related to the heated area. This leads to a heating demand of 137 kWh/m^2·a, which includes the institute halls.

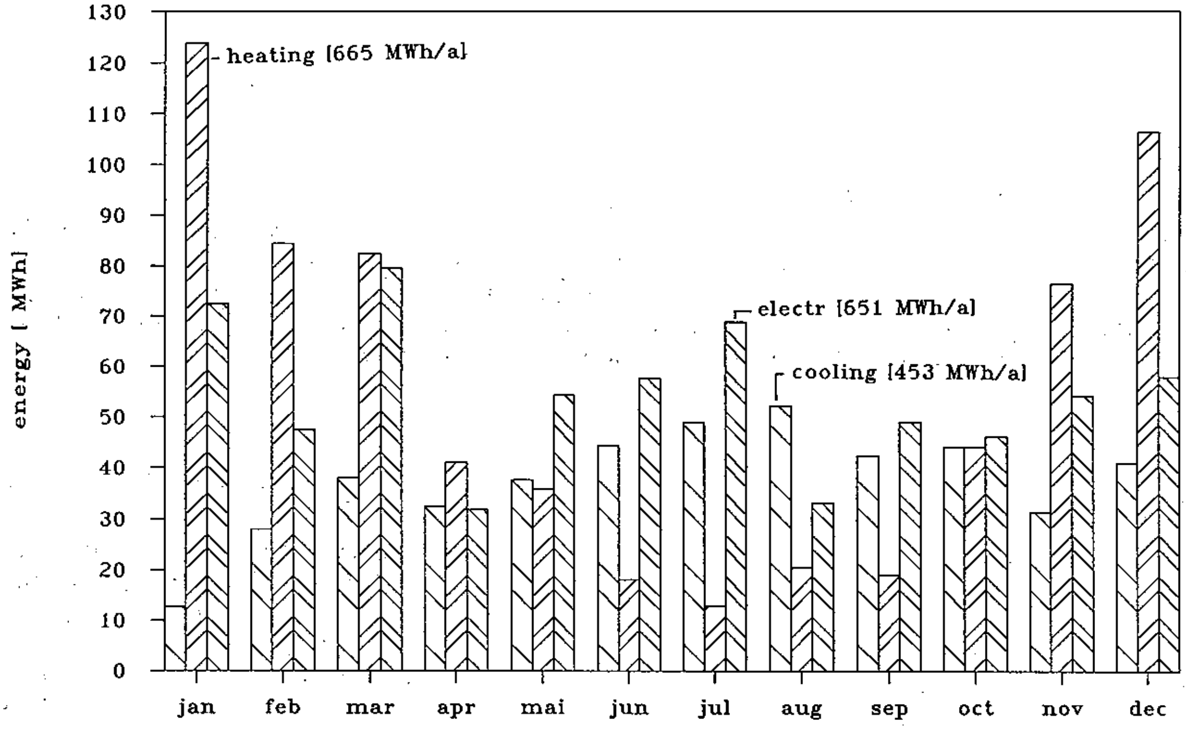


Fig.10: Energy consumption (1987) for heating, cooling and electricity

Table 1: Specific energy demand and costs for the whole building (A_{heat}=4850 m^2)

spec. values in kWh/m^2·a		prices in DM/kWh	total costs
Heating	137	0.10	66 900 DM
Electricity	134	0.27	173 300 DM
Cooling	93	0.14	65 500 DM
for the cooled area (A_{cool}=463 m^2)			
Cooling	978		

Control system

Table 2: Weather data, degree days (according VDI 2067) and heating demand for Stuttgart

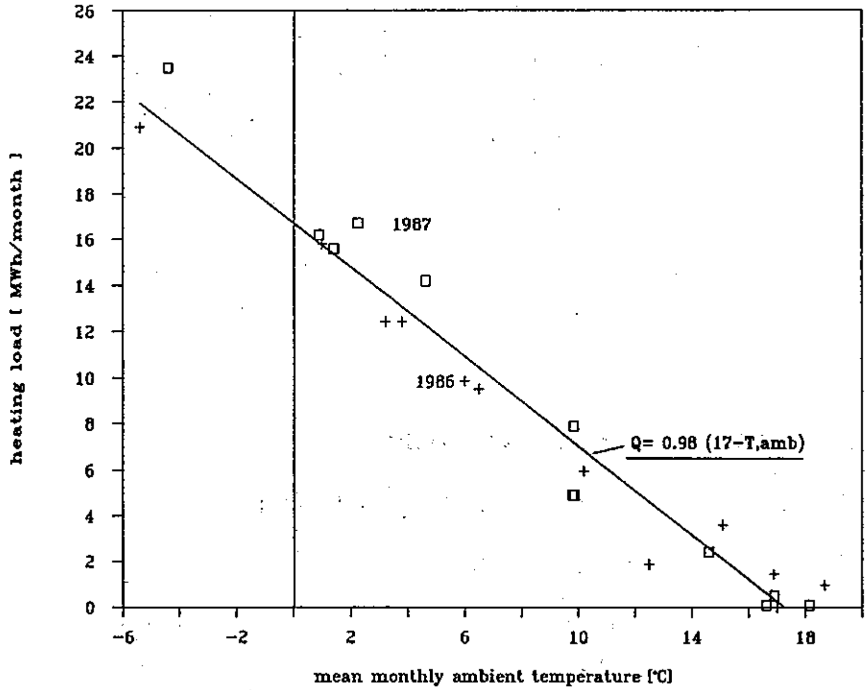
Year	Glob irradiation	Ambient	Degree days	Heating load	Office part		
	[kWh/m²]	Temp.	K·d	GJ/MWh	MWh	kWh/m²	kWh/m²Kd
1986	1040	9.3	3801	2366/657.2	93.8	68.2	0.018
1987	930	8.8	3904	2394/665	107	77.8	0.020

At the beginning of the heating period 1987/88 (September 1987) two changes were made to achieve a monovalent heating system. The feed of energy from the cogeneration plant was blocked and the overnight room temperature setdown was switched off to avoid high peak loads in the morning.

As the comparison of the years 1986 and 1987 in Table 2 shows, the overnight room temperature setdown had no influence on the heat demand of the system in a building as massive as this one, except that switching off the setdown decreased the peak load. This is important to note when planning the size of a heating system and for an application of heat sources with smaller peak fluxes.

The office part

The seperate office part of the ENTE-building has no cooling system and a heating system set up for low temperatures in the range of 50/30 °C. Because there are only offices in this part of the building, there are no additional internal heat sources other than lighting and possibly personal computers. All offices face east, to prevent overheating around noontime. In fig.11 the monthly heat consumption is presented as a function of the monthly mean ambient temperature for 1986 and 1987. A linear polynominal regression of all values corresponds to:



$$Q_{LOAD} = 0.98 * (17\ °C-\vartheta_{amb})$$

where QLOAD results in MWh/month, if the unit of the mean monthly ambient temperature is °C. The mean overall heat loss coefficient of the office part - including transmission and infiltration losses - is about 1 W/m²K.

Fig.11: Monthly heating load versus ambient temperature (1986/1987).

Heat sources in the office part of the building

Figure 12 shows the monthly heat loads split up into a direct solar, storage and electricity consumption. Direct solar energy from the absorbers to the load, energy from the storage and electricity are covering the monthly heat demand. The sum values for the whole heating period 1987/1988 are presented in fig.13 as a flow diagram. They show a mean efficiency of 31 % for the unglazed collectors. Only 6 % of their gains are used in the direct connection all the rest is used to charge the storage. Of this charged heat a ratio of 85 % is used which is a very good result. This is made possible through the heat pump discharge which allows storage temperatures below the temperatures of the surrounding ground. This causes heat fluxes from the ground to the storage in reversed direction of the heat losses during summer. The mean COP-value of the heatpump is 3.0.

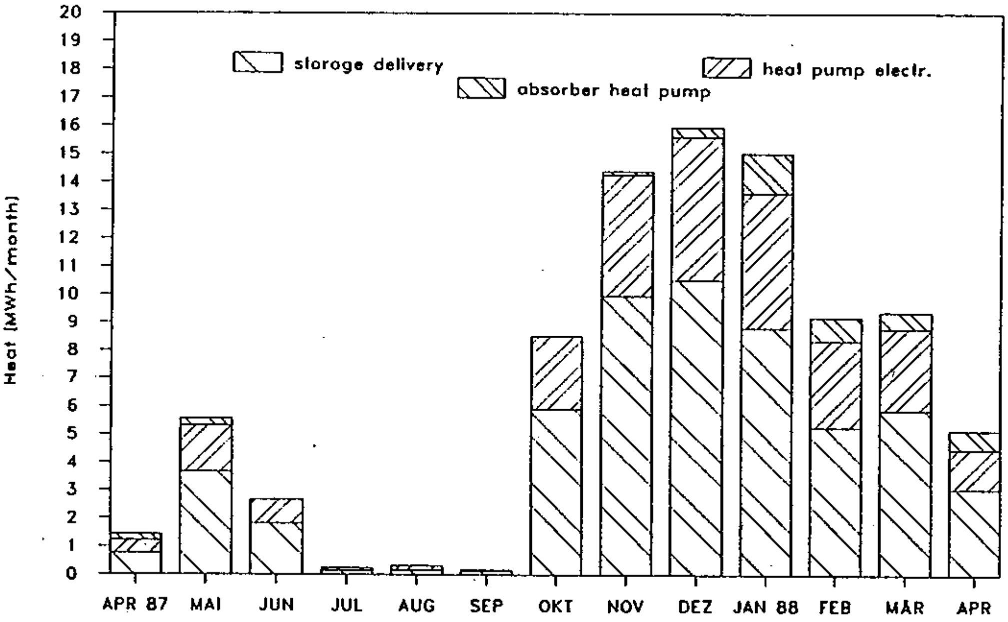


Fig.12: Energy sources of the office part

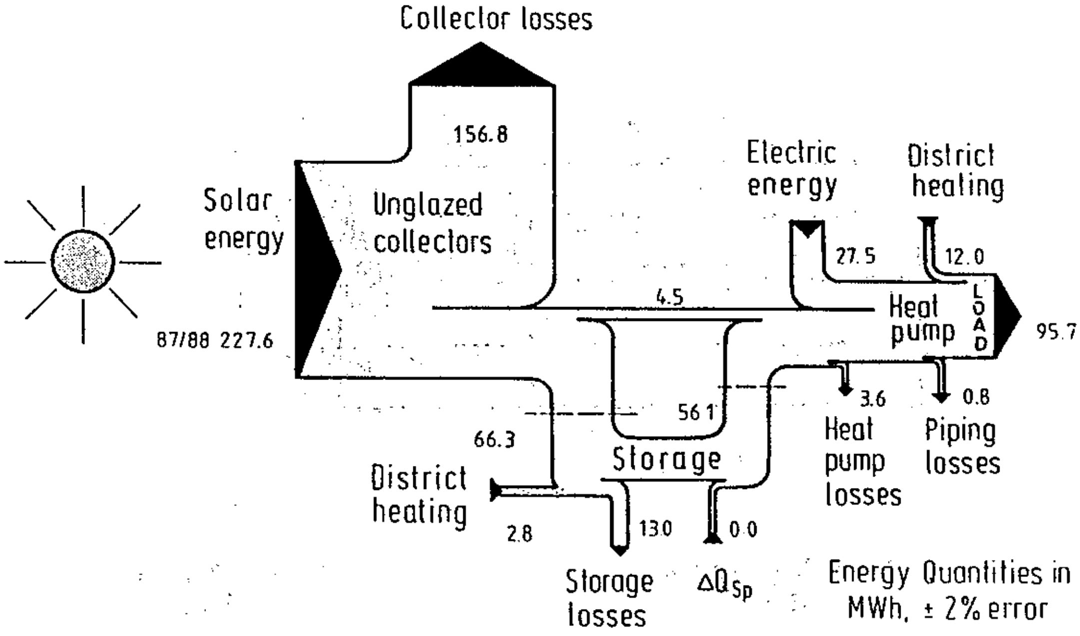


Fig.13: Diagram for the heating period 1987/88

Comparison with other office buildings

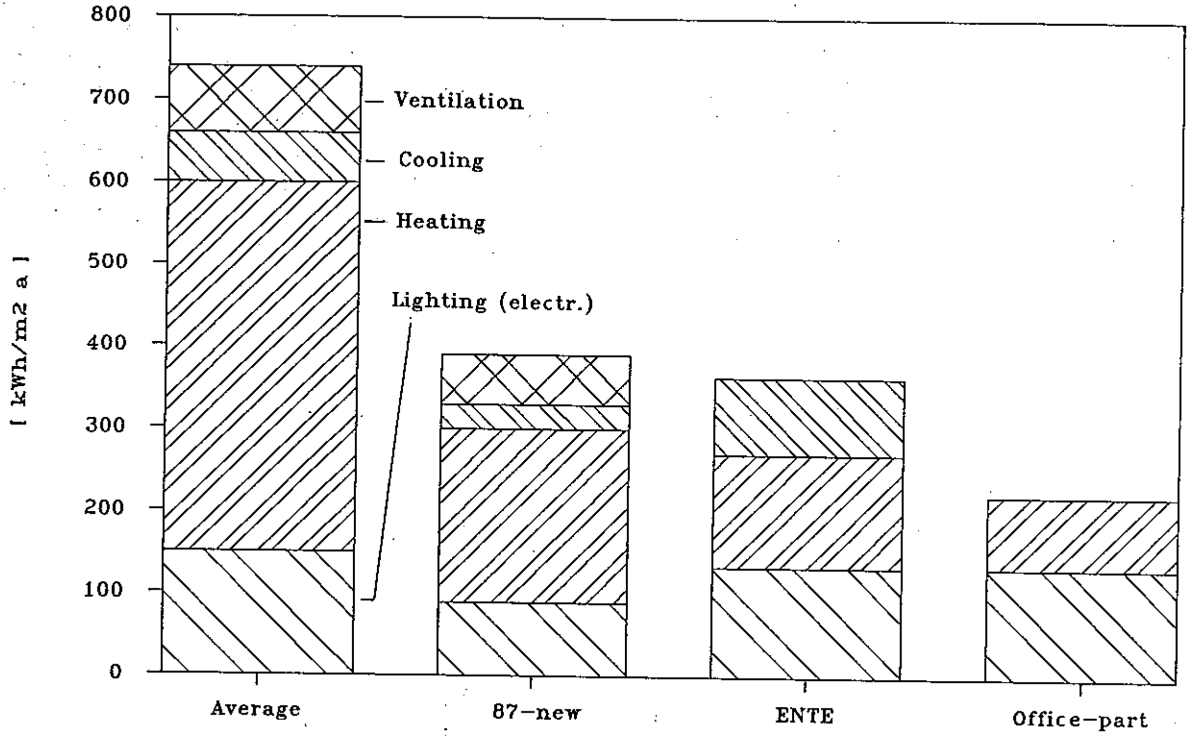


Fig. 14: Energy consumption of German office-buildings

A comparision of the whole ENTE-building and of the seperate office part with other new office buldings erected in 1987, as well as with an average of existing office buildings clearly demonstrates the advantages of a well insulated building. The annual fuel consumption for heating the office part was 30 % lower than the calculated value following VDI 2067. Since without further detailed measurements this value could not be attributed exclusively to the solar gains, another detailed study of two offices was conducted (fig. 15).

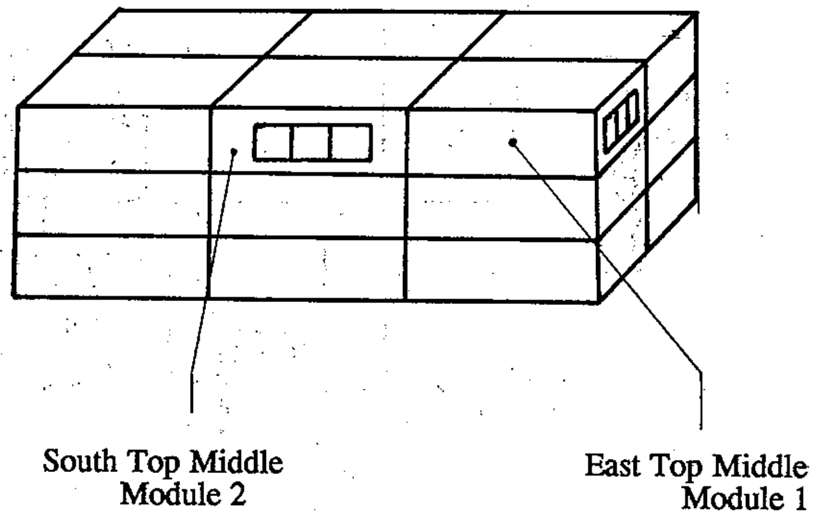


Fig. 15: Position of the modules

MEASUREMENT RESULTS OF THE TWO OFFICES

To investigate the influence of orientation, user profile, size and heating system two different offices in the laboratory part were chosen for a detailed monitoring. Figure 15 shows the position of the two offices in the building and fig.16 the size of module 1 which is used as a library and meeting room for the department. Its glazed facade is oriented to the east and the room is heated with radiators placed at the window front. The room is used mainly for group meetings on Monday mornings and during lunch breaks. During normal office hours the room is rarely occupied. Internal gains are only lighting, a fax machine and the occasional occupants.

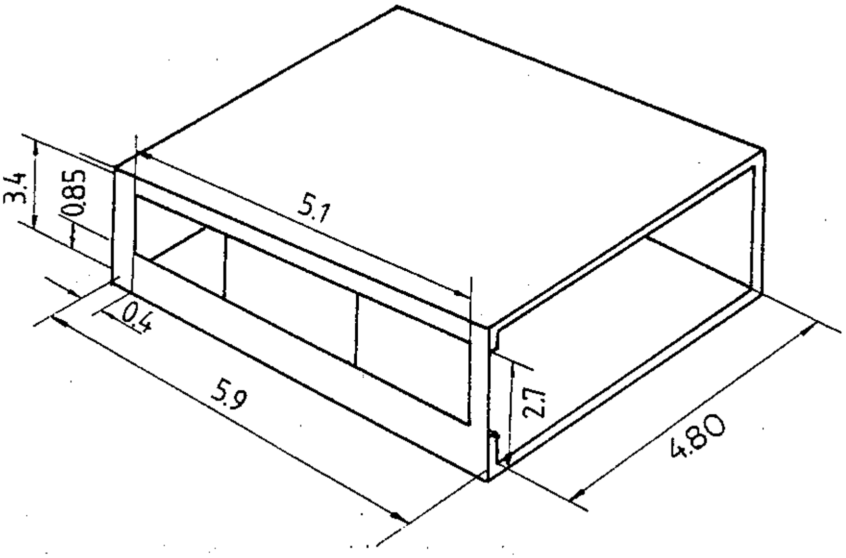


Fig. 16: Size of module 1

Library	
Ground area	28.3 m²
Window area	6.1 m²
U·A (amb)	54.7 W/K

As a contrast, the second office (fig.17) is south oriented, with an air conditioning system and was unoccupied during the monitoring period. The measuring equipment is described in fig.7. There were no internal gains and the infiltration rate was measured at only 0.08 $^1/h$ with the air conditioning shutt of. During air conditioning the infiltration rate increased to 0.8 $^1/h$. This is mainly caused by the untightness of the system because the fresh air delivery was closed. On the other hand an underpressure to the ambient was measured during the running times of the air conditioning system. As a result from the measurements of the wind pressure and the infiltration rate it was determined that for this airtight facade no connection between this two values could be found.

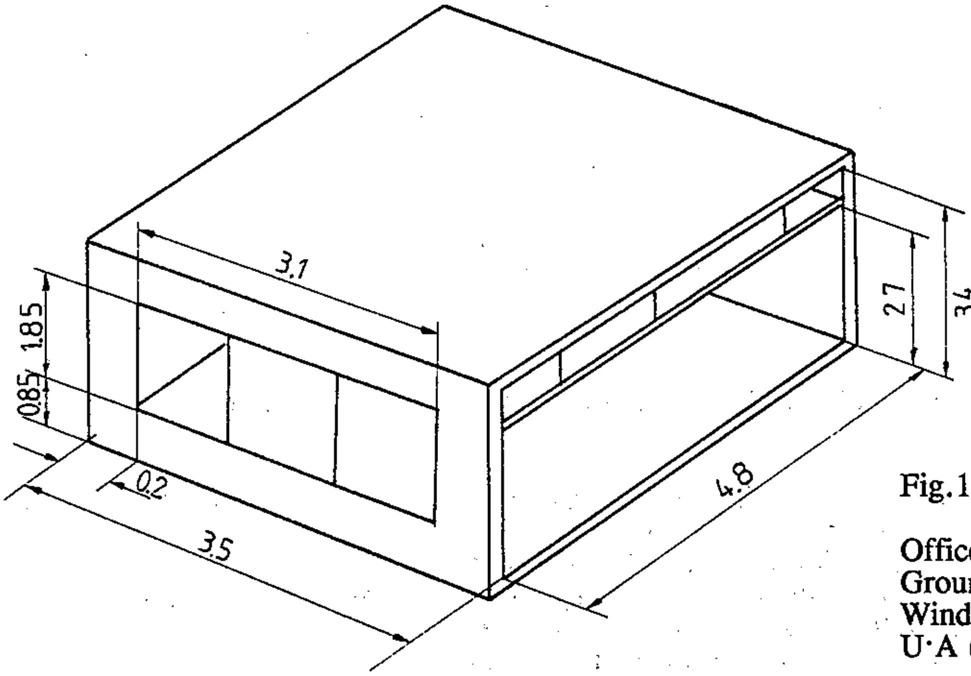


Fig.17: Size of module 2

Office	
Ground area	16.8 m²
Window area	3.74 m²
U·A (amb)	26.8 W/K

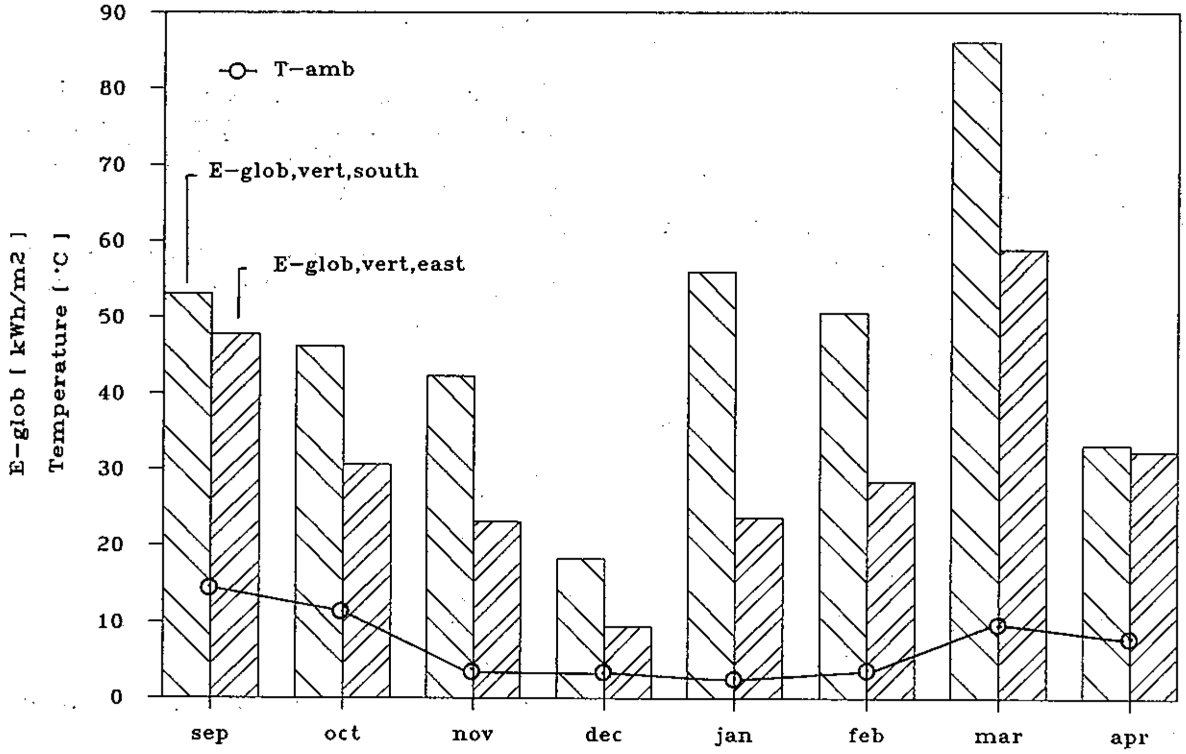


Fig.18: Weather data for the two orientations during the last heating period

To get an impression of the weather data for the heating period 88/89 fig.18 documents the outside global solar radiation on the vertical south and east facades and the ambient temperature on the roof. For the heating support the transmitted ratio of this radiation is important, which depends on the incidence angle. Figure 19 gives the monthly mean values for the two window facades during the heating season.

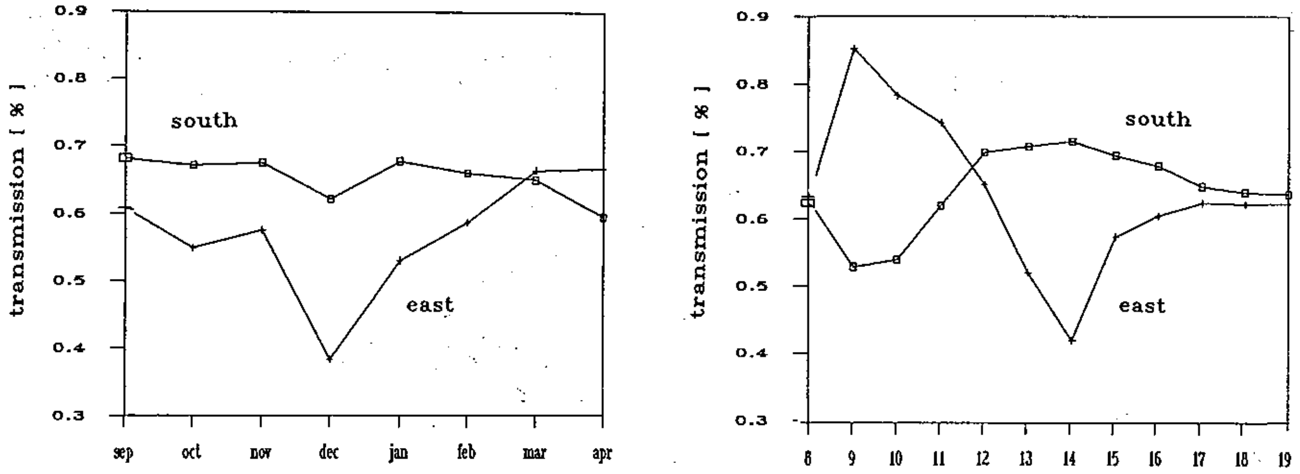


Fig.19: Monthly mean values of the window transmission and a daily profile for October 13th

Significant is the very low value for the east orientation in December caused by the low declination of the sun and a high ratio of total reflection. In addition fig.19 shows one daily profile of the transmission ratio for a sunny day in October. This underlines the good transmission values of the east orientation in the morning which correlates with the heating of the rooms. The low values for the transmission in the evening are the values for the diffuse radiation because the ratio was measured by the ratio of the global radiation.

Heating use and solar gains for the module 1

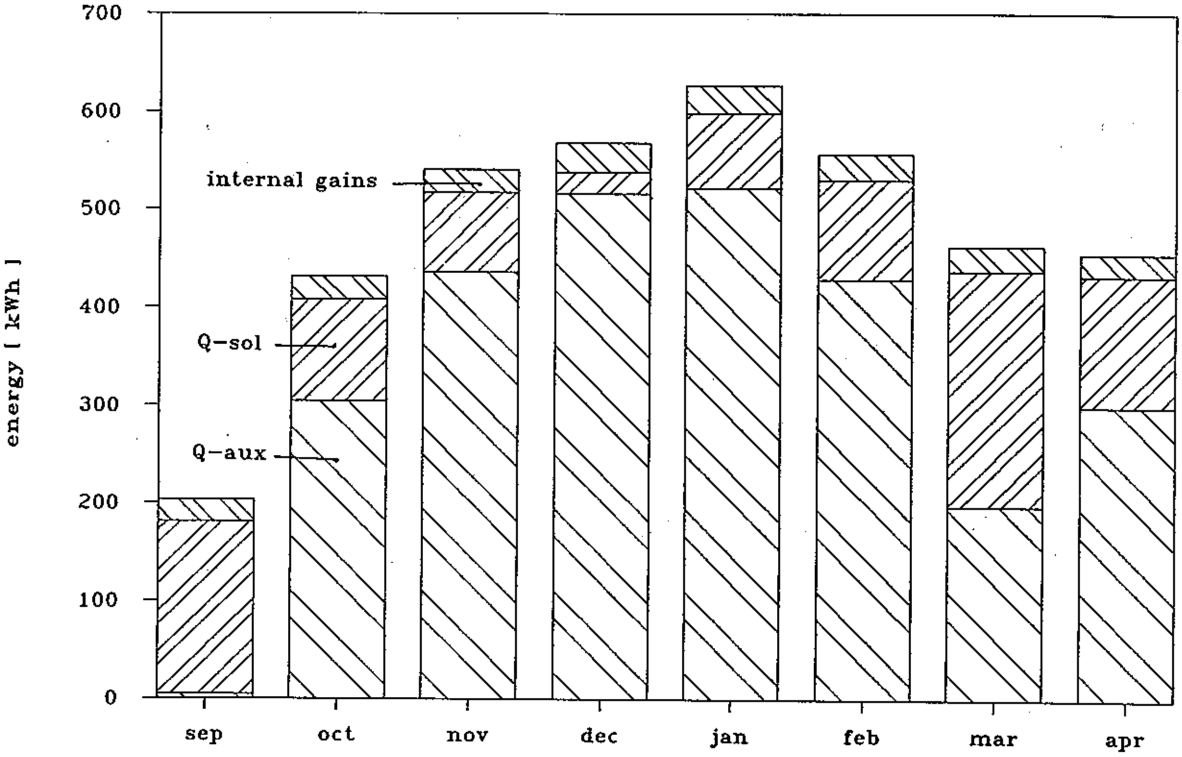


Fig.20: Heating consumption, internal gains and solar gains through the library's windows (facing east, measured inside)

The energy load of the three different sources, i.e. auxiliary heating system, internal gains by lighting and persons and the solar gains through the east oriented windows are documented in fig.20 in monthly sums. The results show a big solar fraction during the transitional seasons. In December and January only a small part of the heating load is covered by the solar gains, which can be explained by the very low radiation and transmission of the glazing for the east orientation during these months (compare fig.18 and fig.19). The internal gains caused mainly by the occupants during the lunch breaks and meeting hours reach only about 5% of the total heating load. There are only a few hours in September and March (in total 26) with room temperatures rising above 24 °C. In these cases the solar gains can not be usefully employed but cause overheating of the rooms. This shows the advantage of an east oriented glazing which easily heats up the room in the morning and has no overheating problems in the afternoon. The heavy building construction has an additional influence on overheating prevention. Outside the heating season the manually controlled shading devices are often closed in the morning to prevent high solar gains and transmission during these hours.

The annual numbers show a total heating load of 3 848 kWh or 136 kWh/m^2 related to the heated area. The solar gains which can be utilized almost completely are 933 kWh which means a solar fraction of 25% of the heating load. The auxiliary energy by the radiators is documentated with 2 712 kWh or 96 kWh/m^2. This is more than the mean value of the office building but the library has a very exposed position with three external walls. The heating demand calculated with VDI 2067 using the measured degree days and the U·A value to the ambiance of this module shows 4 136 kWh for the heating season, 8% more than were measured.

Heating and cooling use and solar gains in the air conditioned module 2

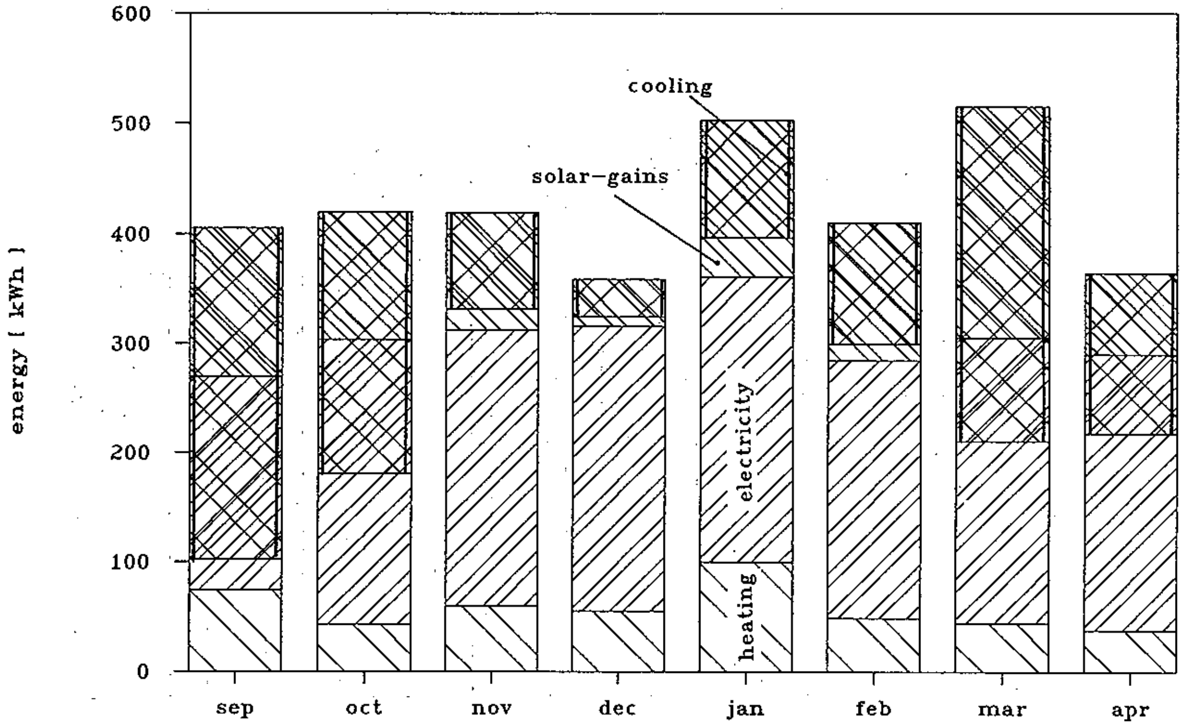


Fig.21: Heating and cooling consumption of the air conditioned office and the solar gains through the windows facing south

As a contrasting example the measured unoccupied office is air conditioned with a room temperature set point of 20 °C. This means that an increase over this temperature level activates the cooling part of the conditioning system. It is necessary to keep this in mind when reading fig.21 which shows the monthly measured energy for auxiliary heating, electricty, solar gains and cooling. For the month of January the diagram is explained in the following way. The positive energy flows i.e. electricity, solar gains and auxiliary heating are assumed. To get an impression of the useful solar and internal gains the cooling load is then subtracted from this sum. This means that only 25% of the solar gains coming through the south facing windows are used for room heating in January. The rest causes an increase of the cooling load. September, October, March and April are examples for how an air conditioning system wastes energy. During these months no solar gains can be used and in March they lead to a tremendous increase of the cooling load. A great part of the internal gains (electricity) which are completely generated by the fan of the air conditioning system also increases the cooling load. This can also be shown by the good agreement of the heating demand calculted by the measured degree days and the U·A-value to the ambiance with the sum of auxiliary heating, electricity and solar gains considered as positive and the cooling energy as negative.

The energy balance over the heating season shows a total heating load of 2 063 kWh or 123 kWh/m^2 related to the room area of 16.8 m^2. This high value is mainly caused by 1 976 kWh electricity for the fan of the air conditioning system. The solar gains entering the room reach a total of 951 kWh, yet only about 10% of them can be used. All the rest and part of the electricity (internal gains) cause the cooling load of 1 330 kWh which is 79 kWh/m^2. The sum for the bought heating energy usefully employed (electricity and auxiliary heating minus the cooling) documents a low heating load of 66 kWh per square meter office area.

Comparing the solar gains per square meter window area depending on the orientation render 254 kWh for the south and 153 kWh for the east orientation. This must be seen in relation to the thermal losses which are 226 kWh for the heating season.

SIMULATION

Goals

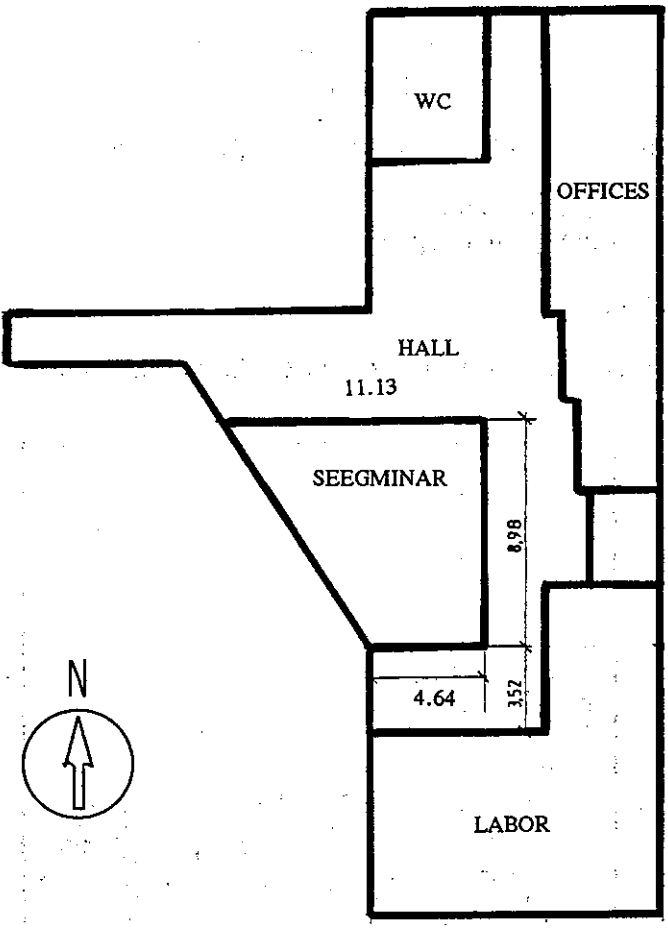
The detailed simulation of the office part of the building with a multizone building programm was used to examine:

- sensitivity studies of various system parameters, with the scope of the building and not the heating system.

Simulation program

For the following sensitivity studies the simulation program TRNSYS was used. This modular program, developed at the University of Wisconsin, contains up to 70 different system modules, each describing one component like a solar collector, a pump or a window. The Type 56 is the model of a muiltizone building. The thermal behaviour of the walls is calculated using the transfer function method of Mitalas. For each wall type these functions are determined by a preprogram.

For the office part of the ENTE building the model is used with 12 different zones. In fig.22 the zoning is sketched for the ground floor of the building. The seminar room called SEEGMINAR was used for the validation, by comparing measured and calculated values.



Building data:

total area	1 589 m^2
heated area	1 375 m^2
total volume	5 566 m^2
envelope	1 558 m^2
total outer surface (excl. windows)	681 m^2
total glazing area (=25 %)	385 m^2
roof area	492 m^2

Fig.22: Zoning of the ground floor

Model description

Distribution of zones: The building was distributed into 12 zones.

2 seminar rooms 71 m^2 each	142 m^2
2 laboratories (104 m^2, 84 m^2)	188 m^2
2 office complexes (containing the 9 different offices)	228 m^2
2 sanitary rooms, cleaning room	155 m^2
3 staircases	489 m^2
2 storage rooms	163 m^2

Layers of the walls: The external walls consist of:

1.2 cm gysum board
17 cm concrete
8 cm insulation
4 cm air gap
12 cm brick

The mean transfer coefficient was determined at 0.34 W/m^2K.

Internal load: lighting in the morning and evening hours
occupants and personal computers following the profile

Air change rate: Daily profile 8 am - 5 pm 1 $^1/h$
5 pm - 8 pm 0.25 $^1/h$

Set point heating: individual control, normal 20 °C, no night set back

Weekly profile: Monday - Friday occupied
Saturday - Sunday unoccupied

Climate data: Measured values

Validation: against measurements of one zone and the whole building

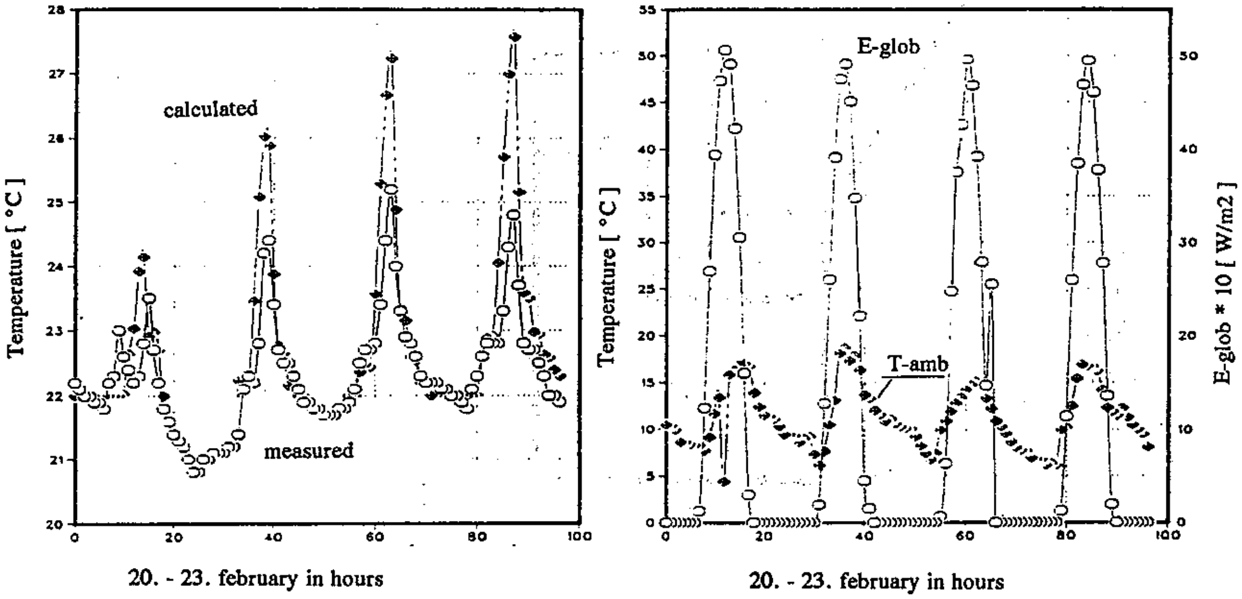


Fig.23: Temperatures in the seminar room measured and calculated and the weather data

Model description

Distribution of zones: The building was distributed into 12 zones.

2 seminar rooms 71 m^2 each	142 m^2
2 laboratories (104 m^2, 84 m^2)	188 m^2
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Set point heating: individual control, normal 20 °C, no night set back

Weekly profile: Monday - Friday occupied
Saturday - Sunday unoccupied

Climate data: Measured values

Validation: against measurements of one zone and the whole building

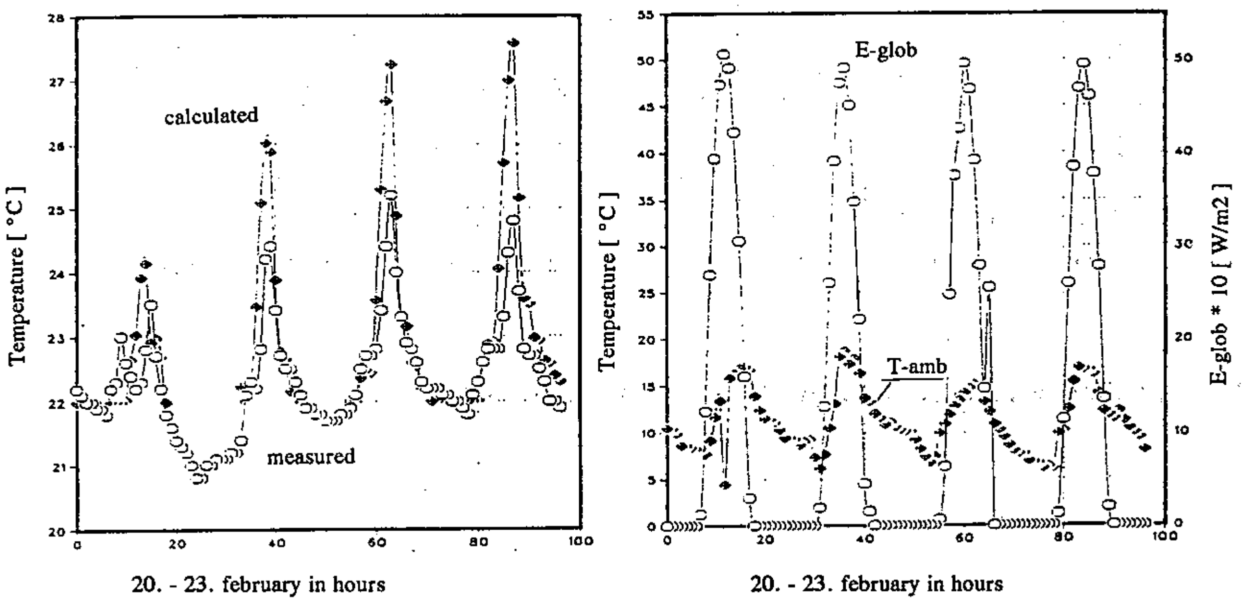

Fig.23: Temperatures in the seminar room measured and calculated and the weather data

Validation

To get an impression of the quality of the modelling the temperature profile of the seminar zone in the ground floor calculated with TRNSYS is compared to the measured temperatures and printed out in fig.23. There is a good agreement during the night time and the early morning. But after noon the increases of the temperature and the maximum temperatures in the model are higher than measured. This can be explained by the overestimation of the solar gains in the original building model which calculates the windows with a constant transmission. Changing the source code the new version of type 56 contains the calculation of the transmission coefficient depending on the incident angle and glazing type. This change and the increase of the thermal capacity of the zone air node by the thermal capacity of the furnitures leads to the measured values.

As the second step of the validation the measured space heating energy load of the whole office building - all 12 zones - is compared to the calculated values. Fig.24 documents the energy consumption in monthly sums for the heating periode 87/88. In general there are only small differences which may be caused by special user effects like christmas parties or holidays. The total heating load for this heating periode 87/88 differs in the range of 2% and has a measured value of 86 MWh or 62.5 kWh/m^2.

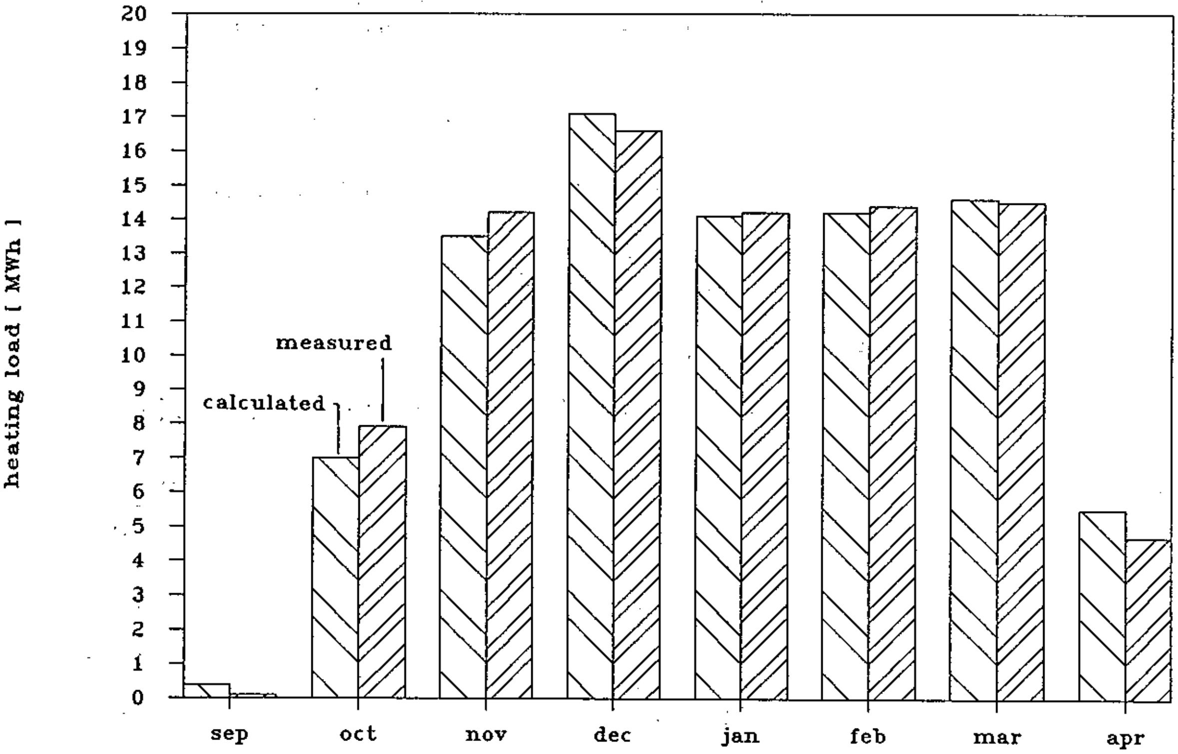

Fig.24: Monthly heating consumption measured and calculated

Parametric studies

After the comparision of the thermal behaviour of the building model to the measured values the model can be used for parametric studies of the building. The sensibility of the following parameters are investigated:

- building orientation
- window areas and window types
- insulation level
- thermal capacity of the building

The reference data of the existing building are:

	heated area	1 375 m^2
-	orientation	East
-	window transparent area	250 m^2
-	window U-value	3 W/m^2 K
-	insulation level	8 cm
-	building capacity	2.1 GJ
	measured heating load	86 MWh

Building orientation

The influence of turning the whole office building from East to West and back to East is described in fig.25 by the change of the heating load. Starting from the reference case with it's main window front orientated to the east the heating load decreases until the orientation reaches the south direction. The model is calculated with an additional venting if the room temperatures rise up over 24 °C. With this strategie an overheating can be prevented. The highest value for the heating load is determined for the north-west orientation which can be explained by the very low glazing area on the north side of the reference building, now looking to the south. The heating consumption for the different orientations is in the range of 10 MWh or 12% of the heating load for the reference case.

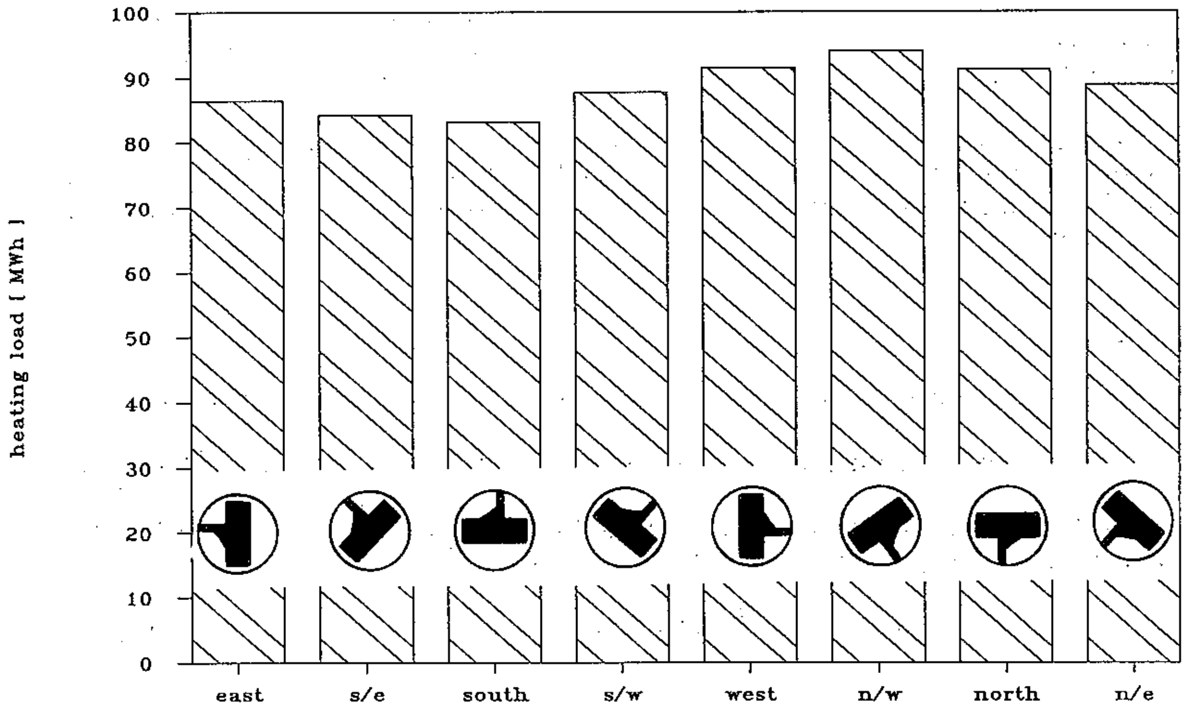

Fig.25: The influence of the building orientation on the heating load

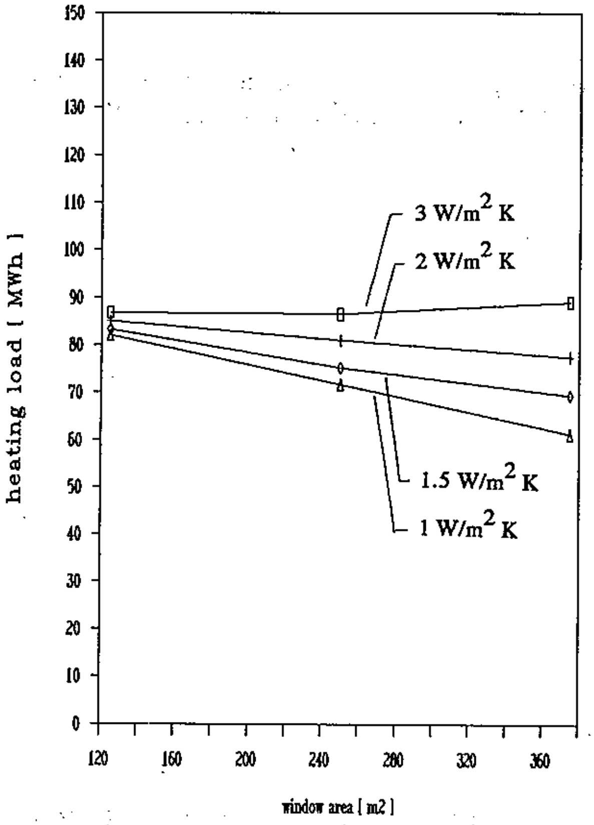

Fig.26: Heating load depending on the window area and type

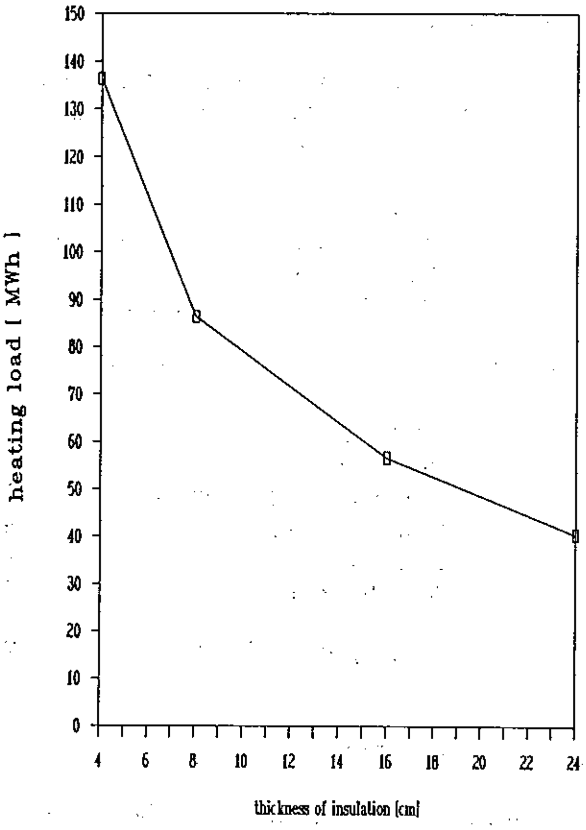

Fig.27: Increase of the heating load with the insulation level

The influence of the two key parameters in the heat conservation concept, the window type and insulation level, on the yearly heating consumption are shown in the fig.26 and fig.27. For the standart double glazing an increase of the window area leads to higher losses which can not be covered by the additional solar gains. If better glazing will be used this additional losses are lower than the solar gains which means a decrease of the heating load. The more important parameter is the insulation level of the walls. The change from the reference value of 8 cm to 16 cm thickness gains 30 MWh per heating season, which is a decrease of more than 30%. For higher insulation levels the savings by a doubling decrease, and the heating consumption approximate to the ventilation losses, which gain more and more importance.

The parametric runs for the building capacity have shown only a very little sensitivity to the heating consumption for the range of 1.05 GJ to 4.2 GJ. In the case of lower capacity than the reference of 2.1 GJ a small increase of the heating load is documented caused by the decrease of usefull solar gains.

SUMMARY

Interpretation of measurements and parameter studies lead to the following conclusions:

- The heating demand of a good designed office building can be in the range of 60 kWh/m^2 a.
- In combination with a electric heat pump a seasonal heat storage covers 67% of this heating load and leads to a bought energy consumption of 19.8 kWh/m^2 a.
- The seasonal storage charged by unglazed collectors during the summer has a storage efficiency of 80%.

Detailed measurements of two offices show:

- Solar gains are measured with 254 kWh/m^2 for a south orientated window and 153 kWh/m^2 for the east.
- The mean transmission for solar radiation for the double glazing was determined with 70% for the south and 60% for the east orientated vertical glazing.
- For the east orientated office room all solar gains are useful and no overheating was measured.
- 25% of the heating load are covered by the solar gains.

For an air conditioned office the results show:

- An air conditioning system has a very high electricity load for the fan of 117 kWh/m^2 a.
- The useful solar gains for a south orientated office are measured with 10%.
- 90% of the solar gains and parts of the electricity for the fan increase the cooling load.
- The cooling load for the temperature setpoint of 20 °C reaches 79 kWh/m^2 a, more than the heating with 66 kWh/m^2 a.

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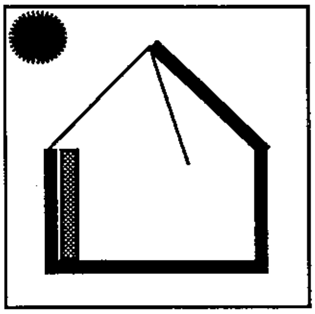
Los Molinos School

Blanco Wall Direct Gain Passive System

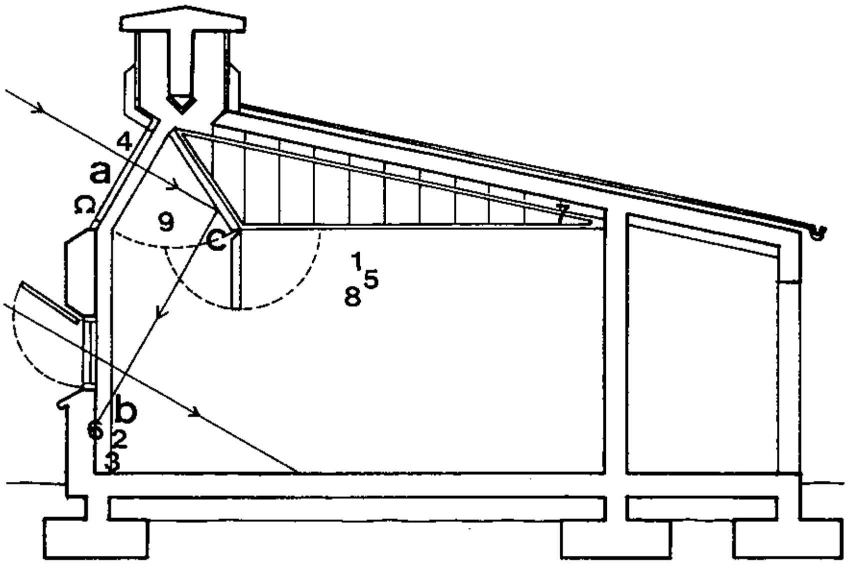
Report prepared by
Alexander Casanovas, Dept. Termodinamica, Universtat de Valencia

0. Introduction

The classroom and laboratories building of Los Molinos School of Environmental Sciences (Crevillente, Alicante, Spain) has been designed as a traditional Mediterranean building including passive solar features. Los Molinos passive systems are not only used as building's heating and cooling systems but also as demonstrative examples of passive solar uses. Due to the very mild climate (1421 annual degree-days, base 20) and high solar irradiation standard (global solar irradiation 2636 MJ/m^2) are the passive solar heating systems in Los Molinos not optimized for heating. The architect must care about overheating of the building more than to care about the best design in such a climate. The school does not require auxiliary heating energy.



The Blanco Wall (BW) is the main heating passive system used in the classroom and laboratories of the building. Its name comes from the designer of the BW, the architect Ignacio Blanco. The BW passive system is based on the heating of the room-side of a thermal mass wall by solar irradiation. Solar energy comes in through slanted windows and is directed to the wall using reflectors included in the window shutters (Fig. 1). The BW windows do not exclude conventional windows and are



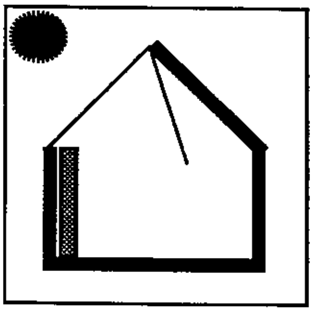


Fig. 1: Section of BW a) tilted windows, b) concrete or water thermal mass in the wall and c) window isolating shutters. The BW shutters include mirrors to reflect the solar radiation on the thermal mass; during the night and hot days the shutters remain closed.

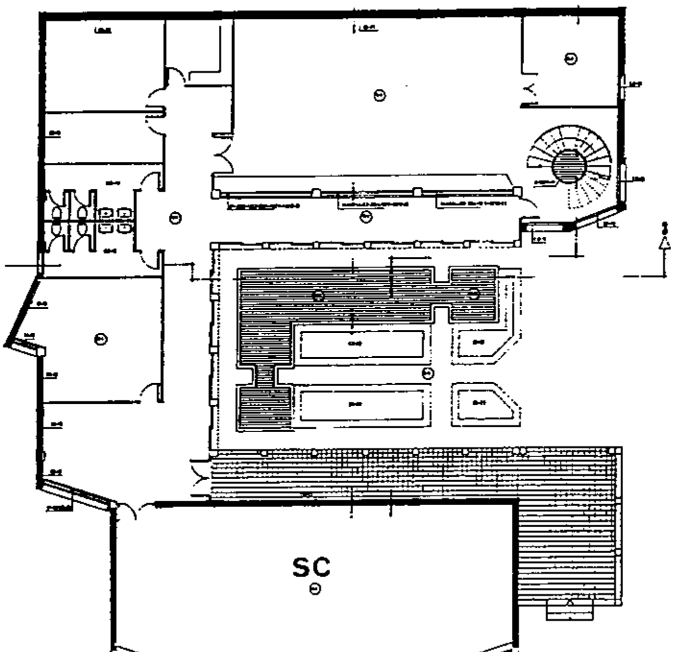
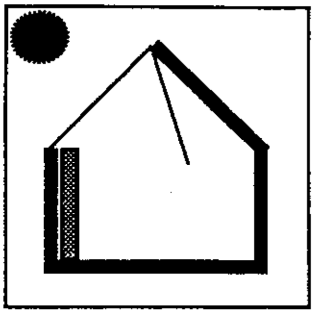


Fig. 2: Plant of Los Molinos classroom and laboratories building. SC: classroom under study.

slanted not only for enabling to direct solar energy on the thermal mass wall with the shutter's reflectors but also to avoid reflection of solar energy on the glazing at low incident angles. The BW concept is simple and avoids most of the drawbacks of more conventional direct gain systems.



One possible disadvantage of passive heating systems is the overheating of building's zones during (and after) hours of peak solar irradiation. Los Molinos BW has two different ways to avoid overheating. The first is merely to graduate the pitch of BW window shutters to an appropriate degree. The second is initiate cross-ventilation opening in part the conventional windows of Los Molinos (of the sliding type). The monitoring of the building shows that the classrooms of Los Molinos never go overheated due to the BW passive system.

The purpose of this study is to assess the energy savings of including the Blanco Wall in the building design, to establish the optimum conditions of design of the Blanco Wall and to evaluate Fanger's Predicted Mean Vote comfort index (PMV) on buildings provided with the BW. The heating effect of BW on buildings located in the Mediterranean area, with a high solar irradiation standard, is of special interest.

1.Project description

'Los Molinos' School of Environmental Sciences was founded by the Social Work of CAM (Caja de Ahorros del Mediterraneo, a savings bank) in 1979. The school imparts renewable energy concepts. Los Molinos consist of a few buildings distributed over a wide nature environment. Most of the buildings are retrofits of former water mills (mill is the english word for *molino*) done by architect I. Blanco. The classrooms and laboratories building is the only new plant building. This building includes several passive solar systems as demonstrative examples of solar passive concepts. The classrooms and laboratories building provides at same time a comfortable working environment for staff and pupils and has a low maintenance cost. The architect, I. Blanco, has integrated in the project passive solar concepts with Mediterranean rural architecture uses to maintain the former environment. He developed a new, aesthetically pleasant passive system fitting the traditional local architecture, the Blanco Wall. The building, designed to be of zero auxiliary energy for heating and cooling, was occupied in March of 1984.

The building is located near Alicante, on the south-east of the Iberian peninsula, 20 km from the coast on a slope 300 m above sea-level. There is no shelter or site obstruction and the building is subject to strong winds.

The building consists of three wings around a patio open to the east; the north wing has two floors and is partially earth sheltered to protect it against north winds. A water pond and a little garden are included in the patio. The west wing is transverse to the other two and joins them. Administrative offices and a workshop are located in this wing. The classrooms are in the south and north wing; the classrooms have only south facing windows.

The Blanco Wall is the main passive system in the building. Ventilation chimneys, a sun-space and a patio open to the fresh summer eastern winds are other passive systems of the building.

Construction is traditional: brick walls, wooden doors, window frames and shelters, and a tiled pitched roof. External walls are provided with fibber-glass insulation. The most part of the glazing faces south. The classroom building of "Los Molinos" has been deliberately not provided with auxiliary systems for heating, cooling or ventilation. Electric energy is used only for lighting with low consumption fluorescent tubes, for some demonstration devices like video and slides projector, and for a low power water pump for the 7 m^2 of solar collectors that provide hot sanitary water.

2. Simulation parametric study of Los Molinos building thermal behavior.

The SUNCODE simulation program has been tried as the more appropriate simulation tool for Los Molinos BW, as it allows the distribution of the solar energy over the inside surfaces of the zones according to specific patterns. SUNCODE is the PC version of the mainframe computer program SERIRES developed by the Solar Energy Research Institute (SERI).

The classroom in the south wing of the building is practically isolated from the rest of the building and includes the BW as the fundamental passive system. This unit, of 111.5 m^2, has been chosen as a convenient environment to test and to simulate the behavior of the BW. The BW can use water tanks or a massive concrete wall to accumulate the solar energy. The south classroom (SC) has only concrete thermal mass walls, but in the parametric study we have evaluated the relative performance of water tank walls and concrete thermal mass walls.

The simulation study compares the SC (Fig. 3) and a similar reference room: a more conventional version of the SC with vertical windows (in the same orientation), white curtains to avoid glare (drawn back if solar global irradiation on the outside vertical is less than 350 W/m^2) and conventional walls replacing the Blanco mass walls. The other parameters, like insulation and overall dimensions, are the same for the BW and reference cases. The global heat loss of base- and reference cases are similar for all cases.

South classroom simulation parameters

k-values (W/m^{2}K):

Rome
0.33 (ceiling)
0.44 (walls and floor)
2.84 (double glazing)

Copenhagen
0.13 (ceiling)
0.28 (walls and floor)
1.6 (triple glazing)

Brussels and Zurich
0.20 ceiling)
0.23 (walls)
0.14 (floor)
1.6 (triple glazing)

Temperature setpoints:

Venting setpoint: 24 ºC
Thermostat setpoint: 20ºC
Thermostat night-setback: 16ºC

Ground reflectance (fraction):

0.26 (Rome)
0.3 (all others)

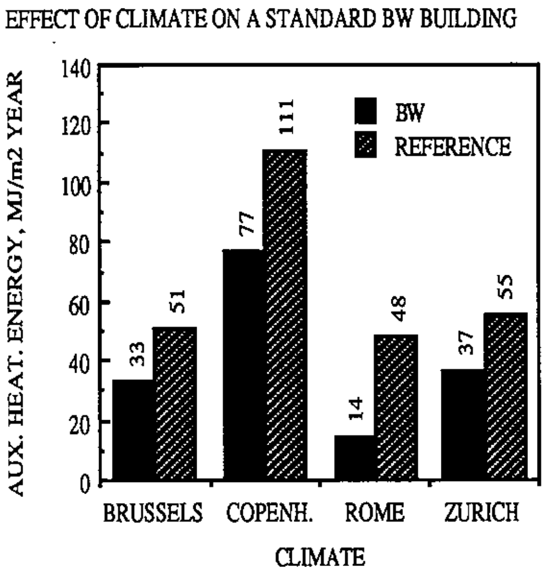
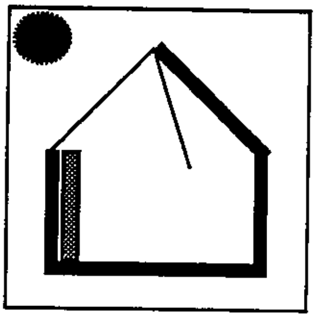


Fig.3: Auxiliary heating energy (AHE) for four European climates.



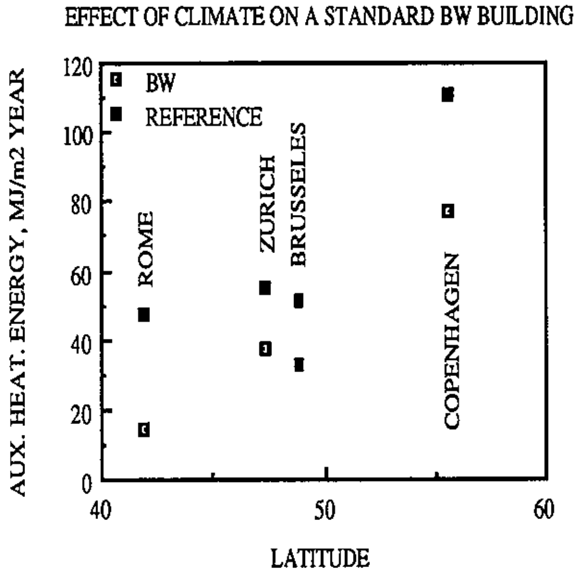


Fig.4: Dependence of auxiliary heating energy (AHE) on latitude. Zurich AHE shows a different trend due to its continental climate.

<u>Design Occupancy:</u>

32 pupils and 1 staff, 80W each.
3.5 m^2/pupil in the classroom

Lighting:
17.45 W/m2

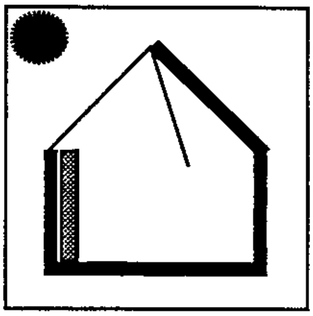
Occupancy schedule:

Rome:
8.00 to 12.00 and 14.00 to 15.45,
Monday to Friday

Brusseles, Zurich:
8.00 to 12.00 and 13.00 to 17.00,
Monday to Friday

Copenhagen:
8.00 to 11.00 and 12.00 to 15.00,
Monday to Friday

Four key parameters have been studied to assess their influence on performance: climate, solar energy distribution among BW and floor, tilt of BW windows and effect of Blanco Wall thermal mass. Four key parameters have been studied to assess their influence on performance: climate, solar energy distribution among BW and floor, tilt of BW windows and effect of Blanco Wall thermal mass. Four European climates[1] have been chosen to compare performance of BW and reference cases: a south-european (Rome), a middle-european continental (Zurich), a middle-european maritime (Brussels) and a north-european (Copenhagen). The shape and dimensions of the building are the same for each of the four climates, changing only the typical insulation level and occupation schedules for each location.



The other parametric studies has been performed for Rome climate. Rome has, like Crevillente, a Mediterranean climate that allows for good performance of BW. An exception in this group is the study of the effect of tilt of BW windows on performance for Copenhagen climate; the goal is to assess the optimum BW window tilt for different latitudes.

Standard parameters for the Rome base case are Rome climate, default SUNCODE infiltration factor, double glazing, original dimensions and shape of Los Molinos SC, night thermostat set-back, water tank BW, 2.27 m^2K/W insulation on walls and floor and 44% of solar energy available falling on Blanco Wall. Case parameters for the other cases are the same except glazing type (triple glazing), insulation level and reduced (half of default) SUNCODE infiltration factor. The following parameters are fixed for all cases: night set-back of thermostats, school-like occupation hours and scheduled U-value for BW windows corresponding to closed shutters during the night hours.

Since the building is a school, temperature and comfort are considered only during occupation hours; the energetic parameters are the values of the whole day. The relative performance of the building is measured through the specific energy (MJ/m^2 year) needed to maintain a minimum temperature of 20ºC during occupation hours[2]7 and 16ºC during the rest of the time. Due to high solar irradiation levels in Mediterranean countries the temperature rises quickly during the day; therefore modeling considers that the excess energy is removed by cross-ventilation if the temperature rises over 24ºC. Figures 3 to 7 show BW AHE dependence obtained from the parametric study.

2.1 Simulation conclusions

- The BW performs adequately in all the European climates studied (Fig. 3). The best absolute results are achieved for Rome and Copenhagen. The best relative saving in heating energy

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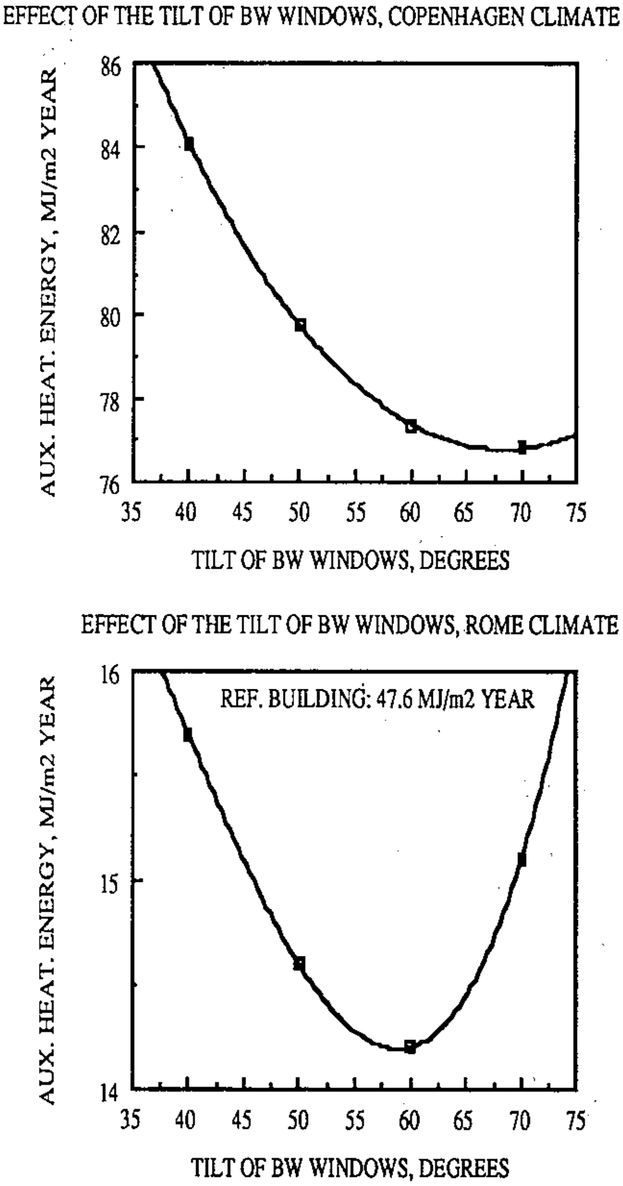
[1] Of the standard set of Task XI Advanced Case Studies.

[2] For the classroom conditions, 20ºC is equivalent to a PMV of - 0.87.



EFFECT OF THE TILT OF BW WINDOWS, COPENHAGEN CLIMATE

EFFECT OF THE TILT OF BW WINDOWS, ROME CLIMATE

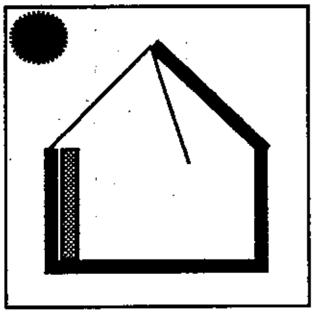


Fig.5: Modeled dependence of the auxiliary heating energy on the tilt of BW windows for Rome and Copenhagen. Copenhagen reference building needs 111 MJ/m^2 year.

is for Rome climate, where the ratio of saved energy to auxiliary energy needed is significant.

- Performance is increased by increasing BW window area up to its geometrical limits.

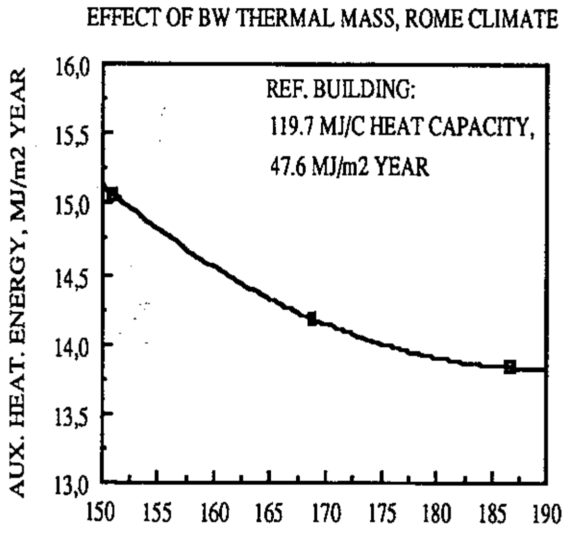
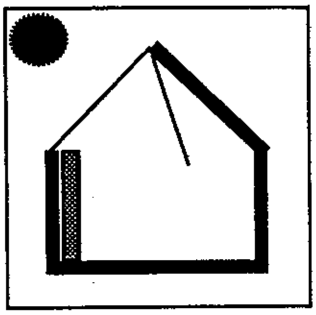


Fig.6: Dependence of the auxiliary heating energy on the BW thermal mass for Rome climate.



- For Rome climate, the water tank thermal mass version of BW performs a little better than the massive concrete wall version.

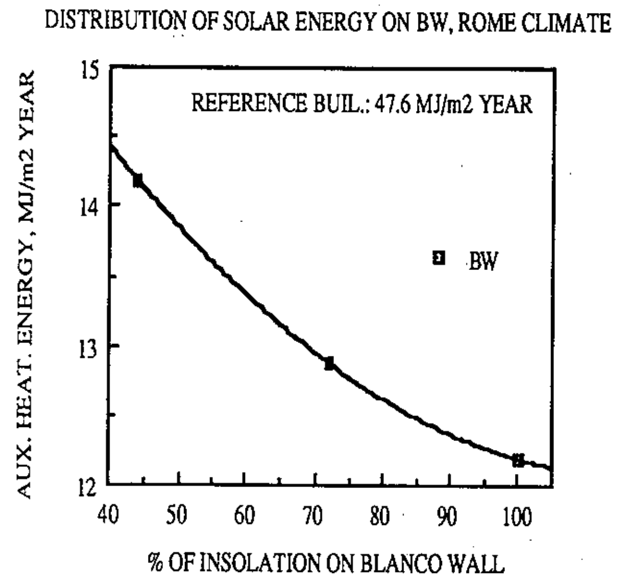
- The auxiliary heating energy (AHE) needed for Rome climate decreases fast with increasing values of insulation thermal resistance and stabilizes for higher values than about 2.5 m^2K/W.

- For Rome climate, the best azimuth for BW facade is between 170 and 180 degrees with some increase in AHE needed by the SC for values about 10 degrees higher or lower. South-east orientation is better than south-west due to earlier heating of the room in the colder morning hours.

- The optimum tilt of BW windows is, for Rome latitude, 59º, and 69º for Copenhagen, but pitch values ± 3º from them give similar results (Fig. 5). This value is about 15º more than the latitude of location.

- The performance (Fig. 6) increases with increasing thermal mass for Rome climate, but stabilizes for water tank thickness greater than 40 cm; a thickness of 20 cm may be sufficient.

- For Rome climate, to concentrate the through BW window incoming solar radiation on BW wall (Fig. 7) is slightly better than to distribute it among wall and floor or furniture (coupling to the air), but not to the levels we can expect from passing from 44% to 100% of incoming solar radiation directed to the Blanco Wall. We can suppose that the BW performs almost equal with limited increasing percentages of diffuse irradiation for given values of global solar irradiation. The point is that for overcast skies global radiation is consequently reduced.



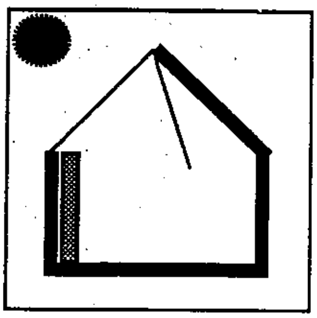


Fig.7: Effect of solar energy distribution among BW, floor and room-air for Rome climate.

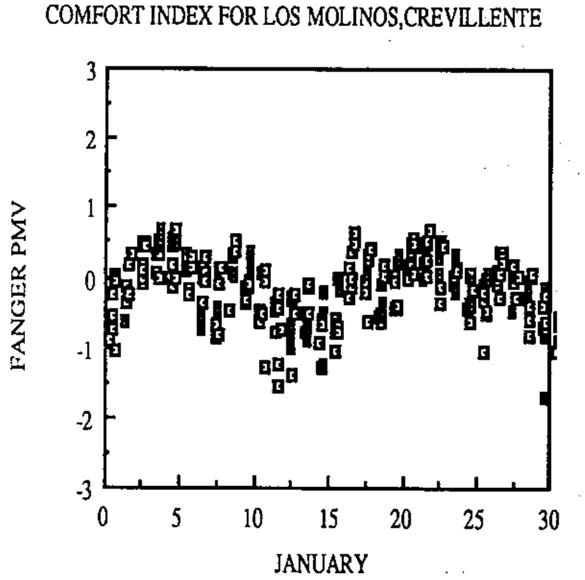
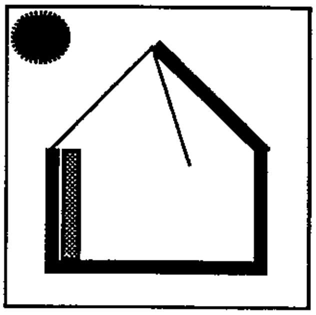


Fig.8: Modeled PMV for Los Molinos School during January.

- The original design of BW includes splitting the south facade in three slightly different azimuths. The benefit of such a design may be a better use of incoming solar radiation along the day. Simulation shows that no splitting the BW is better, but the differences of splitting the BW, or not, are not very marked.



- A non-residential building with BW, increased insulation and glazing area, Rome climate and reduced infiltration rate needs almost no auxiliary heating energy (1.2 MJ/m^2 year).

- Modeling and monitoring shows that for two cases with Mediterranean climates studied (Rome and Crevillente) is possible to have a non-residential building of negligible heating energy, being the Fanger's Predicted Mean Vote (PMV) comfort index of both cases in the +1 to -1 interval of comfort for occupation hours (Fig. 8). The modeled average January PMV is -0.159 for Crevillente climate. Predicted Mean Vote (PMV) has been evaluated for seating people dressing 1 clo.

3. Monitoring

As already said, the passive systems of Los Molinos are mainly demonstrative examples of passive solar uses. Therefore the passive solar heating systems in Los Molinos are not optimized for heating purposes; the very mild climate and high solar irradiation values makes it unnecessary to care about the best design. On the contrary, the architect must care about overheating of the building in a similar climate. Therefore the weight on this building monitoring cannot be in evaluating the performance of the passive heating systems like the BW, but in assessing the uses of the building by occupants and in comparing modeled results with measured data.

The monitoring of the building has been performed during a year using a macrostatic approach and during an additional January month applying the Auto-Regressive Moving Average (ARMA) dynamic monitoring method[1]. A dynamic approach seems necessary due to the influence on thermal comfort of the daily evolution of parameters like temperature and humidity. In the original design the building does not use any auxiliary energy for heating; one of the objectives of the simulation is to analyze the comfort indices for colder climates.

The ARMA monitoring has been performed in controlled and uninhabited conditions, and its goal is to evaluate the benefits of dynamic monitoring of a building over a static one in terms of accuracy (due to controlled conditions) and monitoring costs. Fig. 9 gives a simple (one time step back for driving forces) ARMA fit prediction related to actual measured data. The value of global heat loss coefficient obtained with this fit (595 W/C) is in excellent agreement with the blueprint value (Table IV) of 549 W/K.

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[1] For a description of the ARMA method you can see, e.g., the paper of Rabl.

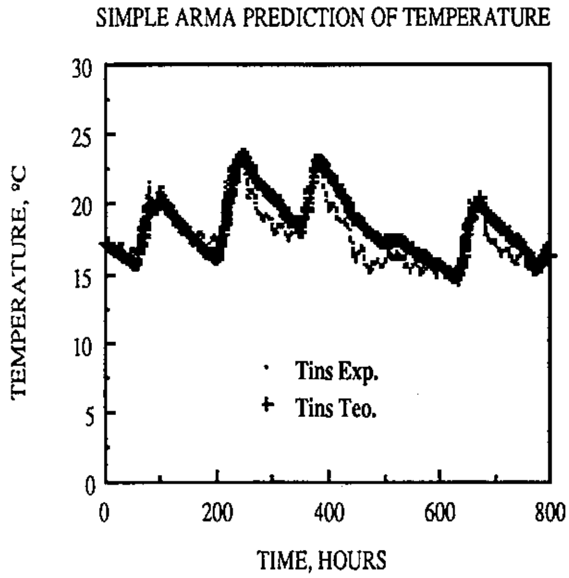


Fig.9: Comparison of simple model (111) ARMA prediction and measured values. Scatter between the two values is due to wind gusts that modify, accordingly, the infiltration rate.

The scatter between ARMA prediction (based on measured parameters) and the actual measured values can be explained by an highly variable AC infiltration rate due to the strong wind gusts prevailing in Los Molinos. We have not been aware of this problem before ARMA monitoring and wind speed has been not measured with the ARMA set-up. We propose accordingly to include wind speed as a driving force in ARMA monitoring.

The year-long macrostatic monitoring has been performed in building's normal-use conditions, not only due to the improbability of controlling the measuring environment during a year, but also to evaluate the uses of the building by occupants. The occupants were, at first glance, using an excess of cross ventilation. Both simulation studies and monitoring confirm that regulated cross-ventilation is the most simple way of limiting inside temperature in Los Molinos BW classrooms. Cross-ventilation at the same time renews inside air in the afternoon hours, as the inside temperature rises.

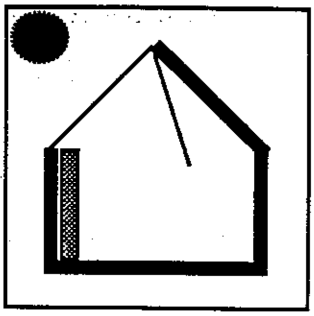
A known weakness of simulation programs is that they use very simple models of solar radiation over arbitrary oriented surfaces, due to the fact that most of them were developed in the previous decade. Several new models are now at hand to evaluate solar radiation using global horizontal and direct beam as input data. A comparison of models with experimental data obtained during a six months period at Valencia, Spain on vertical sensors provided with artificial horizons (Utrillas et al., 1990) shows that the

Table I. Performance evaluation of the whole building.

	EXTERNAL TEMPERATURE	HEATED SPACE TEMP. (AIR)	SUN SPACE TEMPERATURE	HOR. SOLAR RADIATION	DEGREE DAYS (BASE 18)	GROSS HEAT LOAD
UNITS	°C	°C	°C	MJ/m2	°C*day	MJ
JANUARY 1988	15,1	18,1	17	225	69	6548,22
FEBRUARY 1988	12,8	18,3	18	404	135	12811,74
MARCH 1987	15,8	19,2	19,8	515	39	3701,17
APRIL 1987	18,1	21,5	22	547	22	2087,84
MAY 1987	16,6	20,4	21,3	682	60	5694,11
JUNE 1987	24,9	25,8	27,1	745	0	0,00
JULY 1987	25,7	27,2	28,4	710	0	0,00
AUGUST 1987	25,3	27,3	29	772	0	0,00
SEPTEM 1987	25,9	28,3	30,2	556	0	0,00
OCT 1987	20,8	24,4	24,9	315	2	189,80
NOV 87	14	18,1	17,6	289	108	10249,39
DEC 87	14,8	18,9	18,3	216	93	8825,86
TOTAL				5976	528	50108
MEAN	19,15	22,29	22,80			
COLLECTOR AREA = 100,8 M2						
BUILDING HEAT LOSS = 1098						

	INTERNAL GAINS	NET HEAT LOAD	SOLAR CONT HEAT SPACE	SOLAR ENERGY USED/COLLEC. AREA	SOLAR FRACTION
UNITS	MJ	MJ	MJ	MJ/m2	%
JANUARY 1988	985	5563	5563	55,19	100
FEBRUARY 1988	1923	10889	10889	108,02	100
MARCH 1987	1670	2031	2031	20,15	100
APRIL 1987	1670	418	418	4,15	100
MAY 1987	1670	4024	4024	39,92	100
JUNE 1987	0	0	0	0,00	
JULY 1987	0	0	0	0,00	
AUGUST 1987	0	0	0	0,00	
SEPTEM 1987	835	0	0	0,00	
OCT 1987	1670	0	0	0,00	100
NOV 87	1923	8326	8326	82,60	100
DEC 87	985	7841	7841	77,79	100
TOTAL	13331	39092	39092	388	
MEAN					100

Table II. Monitoring parameters



Number of parameters measured: 25
Full sampling: every 2 minutes
Averaging and recording: every 30 minutes

Variables Measured ([ ], location of sensor in Fig. 2):
External air temperature[1], internal air temperature [1] and internal surface temperature [2]
Temperature of accumulating systems [3]
Global solar irradiation on a horizontal plane and on the plane of the tilted glazings [4]
External and internal relative humidity [5]
Thermal flux through walls [6] and ceiling [7]
External and internal [8] anemometry and wind direction
Photometry [9]

Monitored Spaces:
Classroom with concrete Blanco Wall (SC)
Classroom with water tank Blanco Wall
Classroom with attached sun-space
Sun-space
Water tank thermal mass in staircase

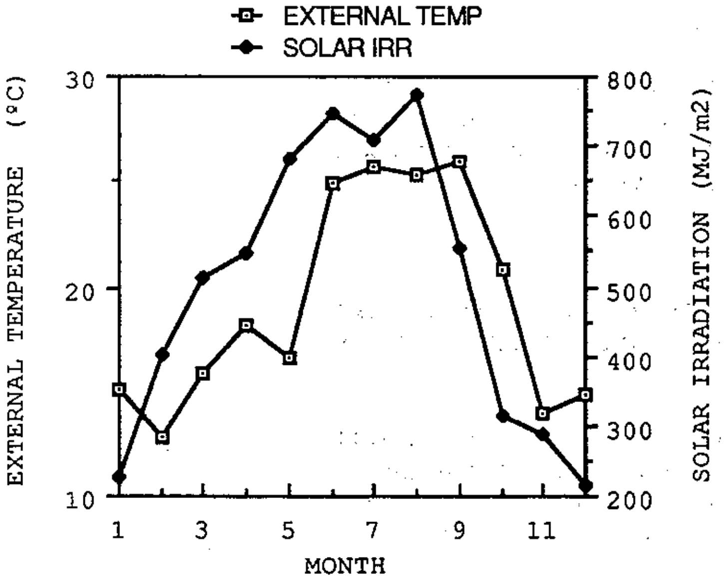


Fig.10: Crevillente average external temperature and global solar irradiation on a horizontal plane.

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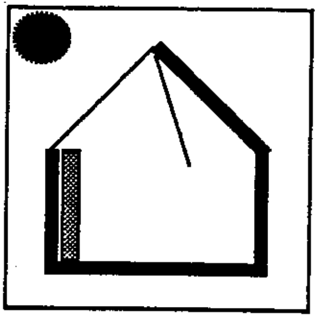
[1] External sensors are situated on the top of the building.

Table III. Los Molinos Building location and dimensions



Latitude and longitude of site: 38º 15' N, 0º 50' W
Floor area: 111.5 m^2
Volume: 431.15 m^3
External walls area (roof excluded): 143.8 m^2
Blanco wall accumulating surface area: 43.9 m^2
Collecting surface area (single glazing 60º tilted windows): 17.8 m^2

isotropic model for solar diffuse irradiation that SUNCODE uses can be adequate for overcast skies, but not for Mediterranean climate: from eight compared models, the isotropic model is the seventh in order of absolute RMS error on south vertical orientation. The effect of the isotropic model on simulation is to underestimate the solar gains through south facing windows, as in Los Molinos case.

3.1 Description of monitoring

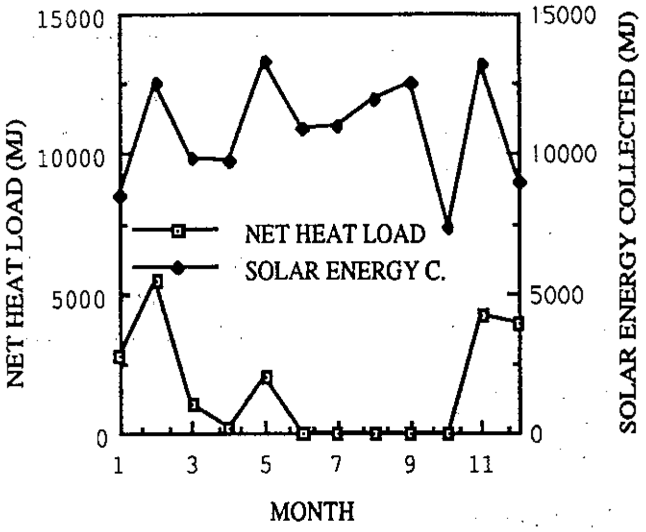
The monitoring details are given in table II. Sensors used are platinum resistance thermometers with four wire connections (screened from radiation if outside), capacitance type humidity sensors, Middleton fluxmeters and pyranometers, LI-COR photometers, a hot-wire anemometer (to measure air speed inside the SC), and a conventional rotating anemometer and vane. Data-acquisition is done through Data-Translation 16 bit, differential input, plug-in A/D converters and a XT PC with a 20 Mb hard-disk. Isolated measures of infiltration have been made with a tracer gas and a spectral gas analyzer. ARMA monitoring has been made with a LI-COR LI-1000 battery-operated datalogger. The pyranometers have been calibrated *in situ* with a precision Eppley PSP pyranometer.

3.2 Heat balance

The heat balance of a room-with-Blanco-wall has been evaluated in a classroom, which is the least closed environment available to evaluate heat balance.

We consider the worst case for thermal loses; the chosen south classroom (SC) presents the most unfavorable conditions for thermal losses. We consider also that the tilted BW windows have their isolating shutters always in the open position.

Analyzed data corresponds to the period March, 1987 - February, 1988. Monthly average values of external temperature and global irradiation on a horizontal plane, corresponding to the same period, are represented in Fig. 10. We can see (Table IV) that the measured values of potentially collected solar energy widely exceed values of the net heat load throughout the winter. We



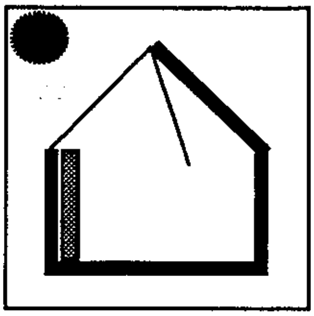


Fig.11: Comparison of neat heat load and solar energy potentially collected for the classroom building of Los Molinos.

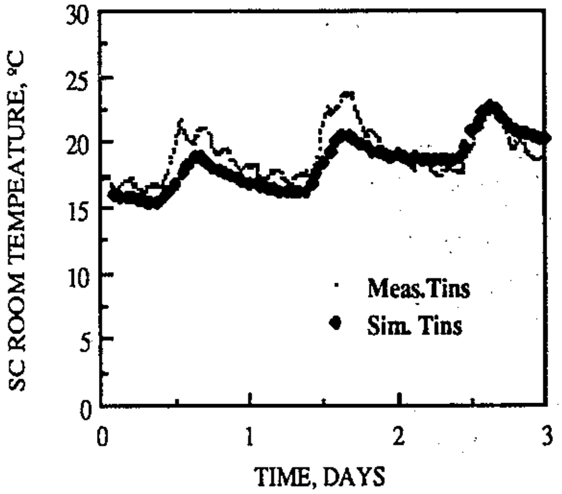
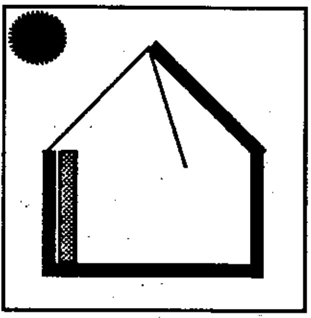


Fig.12: Comparison of modeled and measured temperature for the south classroom of Los Molinos during January.

therefore conclude that the SC needs no auxiliary heating-energy. An analogous study carried out for all the building (C.E.C. Project MONITOR, 1988) shows that the whole classroom building of Los Molinos needs no auxiliary heating energy. A considerable amount of solar energy must be vented out or screened during the summer period (Fig. 11 and Table IV). Most of this period coincides with summer holidays.

Table IV. Los Molinos building thermal parameters.



Thermal Transmittance: (U-values, W/(m^2K)):
Floor: 1.4
Roof: 0.62
Window single: 6.4
Window single with shutters: 0.95
External walls: 0.61
Blanco wall: 0.57
Global heat loss coefficient: 549 W/K

Thermal Capacity (MJ/K):
Primary heat storage: 16.4
Secondary heat storage: 22.2

Accumulative Annual Values:
Degree days (17°C base): 528
Gross heat load: 25046 MJ
Solar irradiation on tilted plane (60°): 6890 MJ/m^2
Internal gains : 6250 MJ
Net head load: 19536 MJ
Solar energy collected: 129635 MJ

Table V. User response[1]

Thermal comfort of classrooms: 2
Aesthetics of the building: 3
Ventilation of classrooms is efficient[2]: 2
Feeling about solar gains (reference: a conventional system): 1
Feeling about lighting gains (reference: fluorescent lighting): 2
The building agrees with traditional local architecture: 1

Fig. 12 compares the modeled and measured data for the same period during the January month. Differences can be explained by two factors:

- the surface convection conductance specified in SUNCODE is a constant, being actually strongly dependent on wind speed. Los Molinos is affected by strong wind guests (17m/s maximum value during January),

- SUNCODE's isotropic solar irradiation model may be not adequate for Mediterranean climates.

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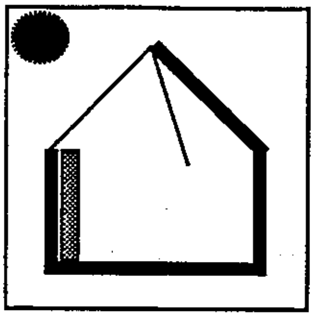
[1] Scale goes from -3 (strong desagree) to 3 (strong agree). 0 is neutral.

[2] One is provided with sunspace, the rest with BW.

3.3 User response



Another form of monitoring is to assess the (subjective) opinion of users about the building, complementing the objective indices like PMV. The type and number of questions have been simplified considering the age and knowledge of pupils. User response relative to Los Molinos, in a subjective PMV-like scale from -3 (strong disagree), 0 (neutral) to 3(strong agree) is given in Table V. In assessing user responses the reader must consider the awareness of pupils about, e.g., traditional architecture.

3.4. Monitoring conclusions

Monitoring of Los Molinos shows that:

- it is possible to have 100% of the heating needs provided by solar energy in the Crevillente passive solar building. Comparison with a modeled conventional building (conventional glazing ratio and conventional glazing distribution over the building; building materials, shape and isolation the same) gives 20170 MJ savings over the year.

- the user response is positive about Los Molinos building.

- simple model ARMA prediction of L value is in very good agreement with the blueprint value.

- cross-ventilation avoids overheating of the rooms provided with the Blanco-Wall.

Finally, Los Molinos passive solar building is cost-effective as regards building cost (4.2 % less than a conventional building) and fuel use (15 MJ/m^2 month of fuel saving in winter).

We can conclude that we have at hand a new and inexpensive direct gain passive system that allows for zero auxiliary heating energy design in Mediterranean countries, and significant reduction of auxiliary heating energy for other climates.

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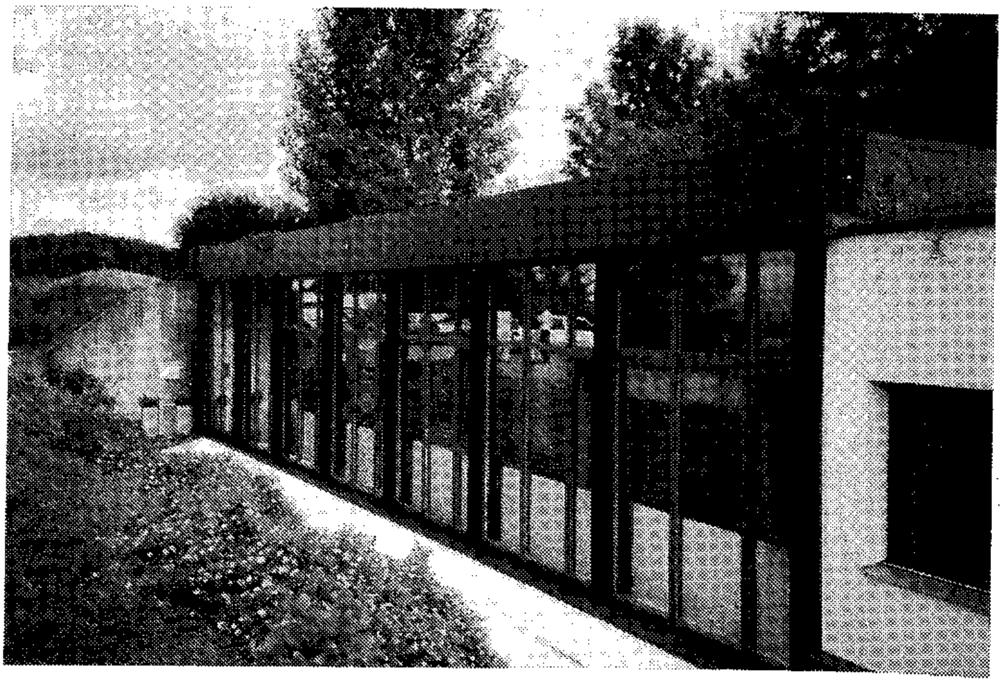
OFFICE BUILDING HAAS + PARTNERS
WINDOW COLLECTORS AND ROCK-BED STORAGE



ABSTRACT

The office building of Haas + Partners, Engineers in Jona (SG), is earth covered and solar heated. The roof and facades to the north and west are earth covered and to the east it has a common wall with a single family house. The south-facing facade has fixed and movable absorbers and interior insulation panels to adapt to different climatic conditions. The spatial layout permits natural thermal zoning. The office building is claimed to have the lowest supplementary heating requirement in Switzerland.

INTRODUCTION

This unique office building was completed in 1980. The client opted for a scheme comprising functional and low energy features and adaptable to changing climatic conditions.

A monitoring project incorporating 70 measurement points provided data on the performance of the building, which was operated as a passive system in 1987/88 and as a hybrid system in 1988/89.

The aim of this advanced case study was:

- To test the efficiency of the combined window/air collector system (temperatures, performance, storage characteristics and electricity needed).

- To record building performance (resulting air temperatures).

- To determine the benefits of earth covering.

- To propose possible optimization strategies for future and more general applications of such systems. For this reason extended computer simulations were made.

BUILDING DESCRIPTION

Location :

The building is situated in the residential area of a small town bordering Lake Zurich on a south-facing slope. There is no solar obstruction. The active solar facade is orientated at 10° west of south. Due to frequent morning fog in winter-time, this provides optimum insolation conditions.

Type :

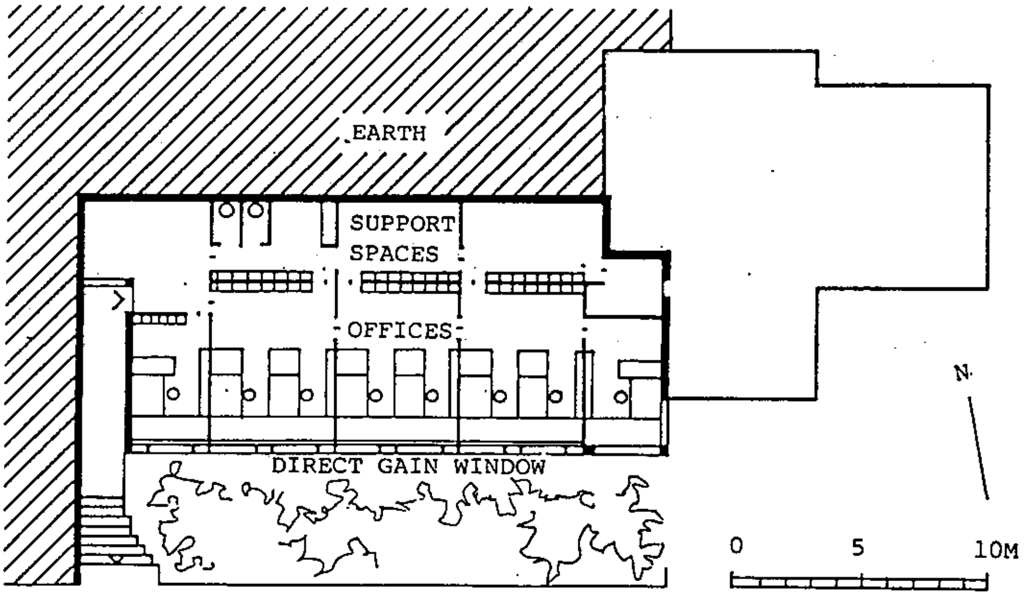
The one-story building, having its main axis in an east-west direction, provides 213 m^2 of utilizable floor area. A row of offices are located behind the front windows. A common area at the rear (a meeting room, archives, kitchenette and toilets) is screened from the offices by shelving cabinets. This simple, functional technique provides natural thermal zoning: offices 20 °C, common area 18 °C, earth surround 10 °C. The ceiling height increases from 2.4 m at the rear to 3.0 m at the front to accommodate the high windows.

Function :

The building is used exclusively for engineering design and consulting purposes and is occupied on working days from 8 am to 5 pm. It is equipped in the usual manner with personal computers, photcopying machine, drawing boards, etc..

Figure 1:

Ground floor

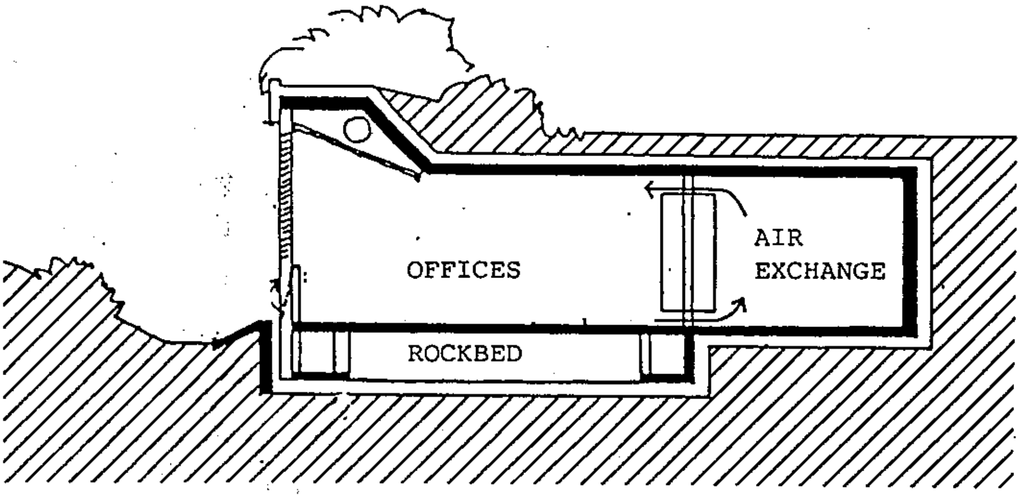


Construction :

All structural elements of the building are of reinforced concrete with 12 cm external insulation on the walls and roof and 20 cm surrounding the rock bed. The windows consist of two separate planes, each with double glazing. Specific heat losses in W/m^2K are: Walls 0.23, roof 0.21, floor 0.17, windows 1.5, windows with night-time insulation 0.35.

Figure 2:

Cross section



Services :

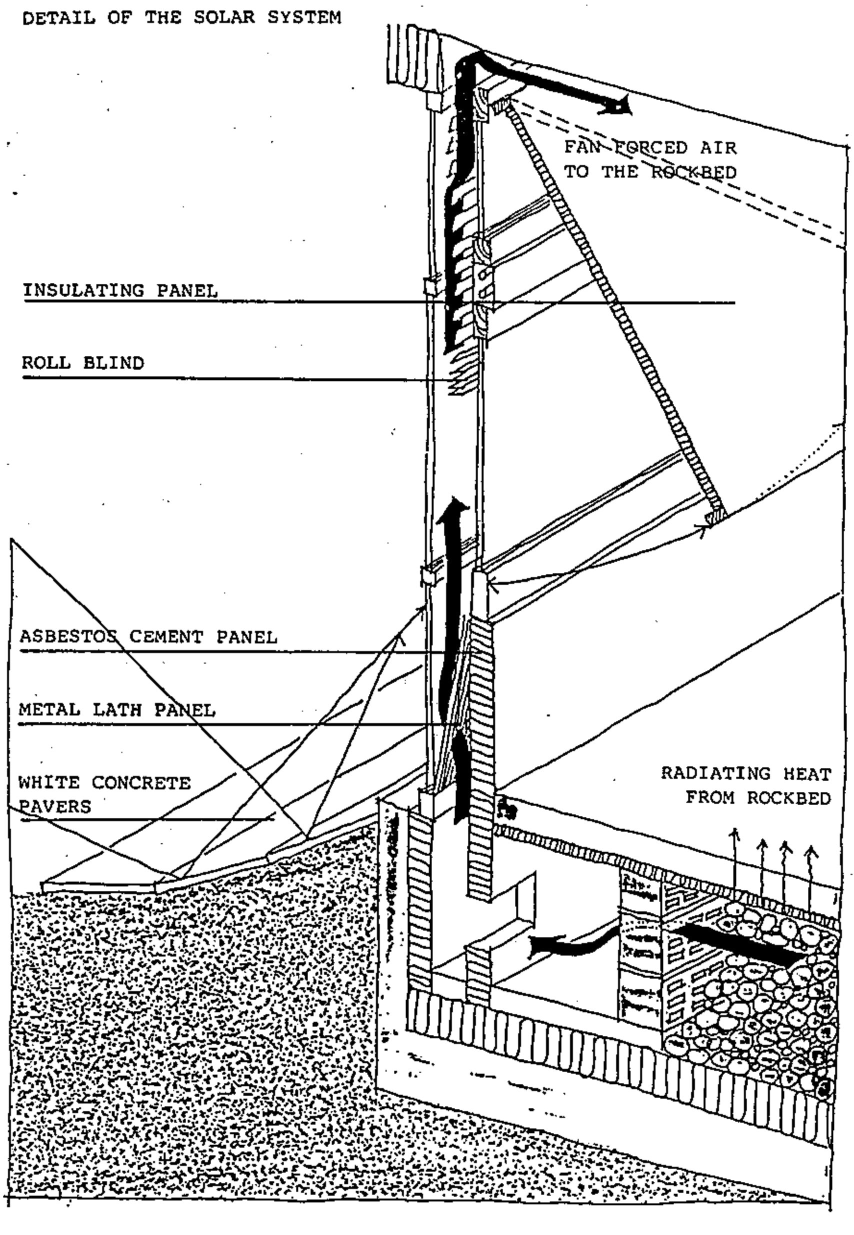
Solar heat is distributed to the building by radiation from a floor slab located above the rock bed. In addition, during December, January, and February, supplementary heat from the auxiliary heating system is distributed via radiators. The thermal inertia of the building serves to dampen temperature fluctuations. Undesirable solar irradiation is excluded from the working areas by slatted roller blinds within the windows. Casement windows - two per office - permit manual adjustment of ventilation and cooling. For those common areas at the rear having no external access, ventilation is provided through slits above and below the partitioning cabinets. A minimum of fan-forced ventilation is also provided. A skylight strip at the top of the partitions allows a modicum of natural lighting in the rear zone.

Solar features :

The hybrid solar system consists of 41 m² of direct-gain windows with movable insulating panels and an underfloor rock bed of 60 m3 with 30 kWh/K thermal mass. The air is sun-warmed in the collector, then fan-forced to the rock bed in a closed loop. The collector performance is enhanced by several features. White asbestos cement panels and concrete pavers reflect sunlight onto the collector to increase gain. The lower absorbers are black metal lath panels, inserted from September until April. A slatted roller blind serves as a movable absorber in the upper part of the facade. It has a bright side for reflection and a dark side for solar absorption, according to need.

Figure 3:

Perspective and functional drawing



System control :

The roller blind is manually lowered as soon as overheating and/or glare occur. A simple controller switches the fan speed to low as soon as the temperature difference between collector and rock bed is more than 10 K. If the sun is strong enough to increase collector temperature to 40 °C, the upper speed of the fan is activated. In the evening, the night-time insulation is operated manually.

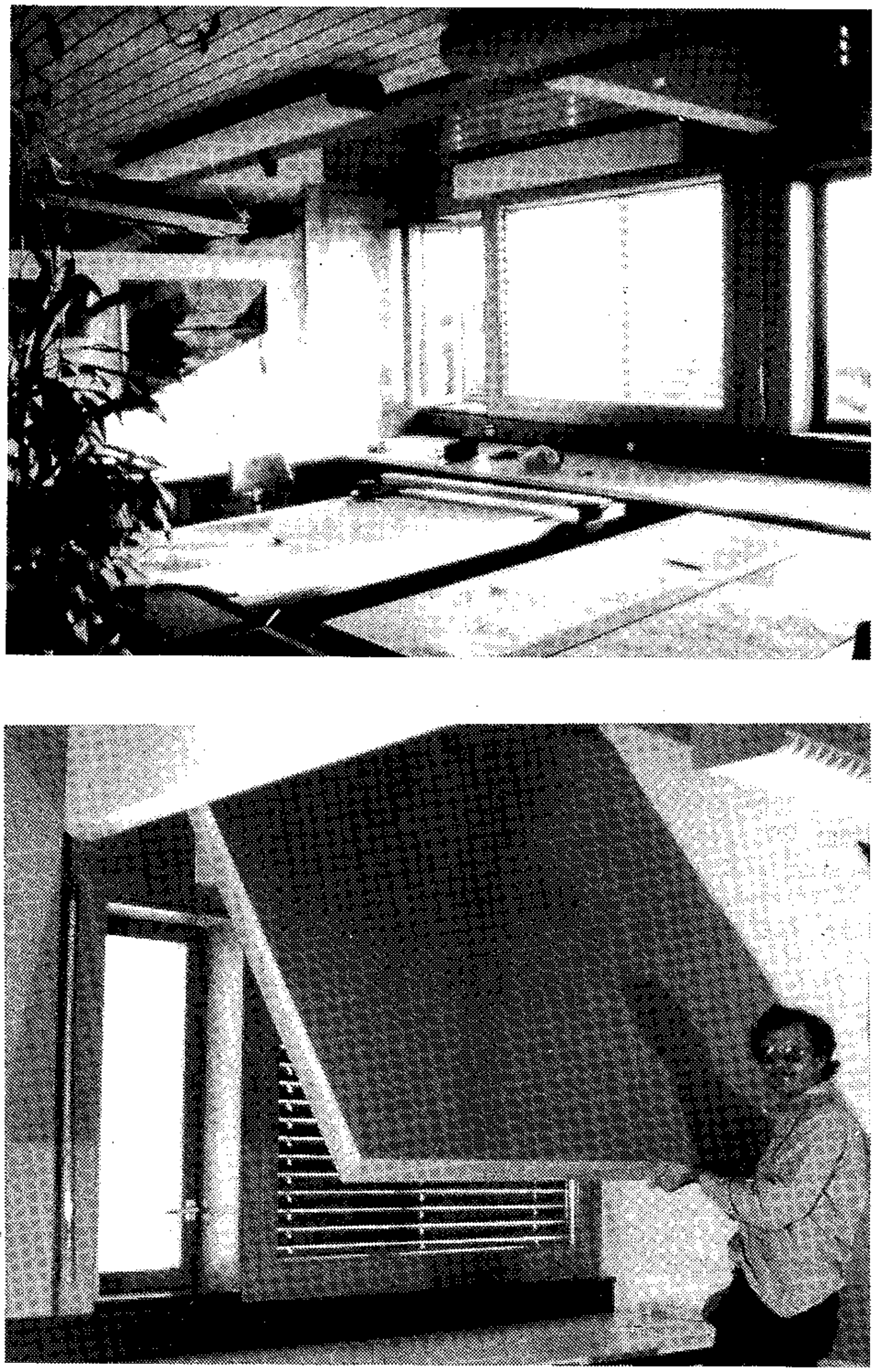


Figure 4: Inside view of office area with window collectors and operation of night-time insulation.

MEASUREMENTS

Objectives/methods:

The measurements were planned with the following objectives

- To test the efficiency of the window collector system (temperature, performance, storage characteristics and electricity needed)

- To compare building performance with passive gain only operation

- To propose computerized optimization strategies and estimate performance in other climates.

A total of 70 values were taken at hourly intervals:

Climate:
- Global horizontal insolation
- Diffuse horizontal insolation
- Global vertical insolation on the collector surface
- Ambient air temperature
- Wind velocity

Earth cover:
- Temperatures at three different depths and locations

Building:
- Air temperatures (9)
- Surface temperatures (4)
- Window opening, status of night-time insulation

System:
- Status of movable roller blind
- Temperatures of collector and rock bed (18)
- Status of two-speed fans

Auxiliary:
- Heat delivered to building
- Electricity used

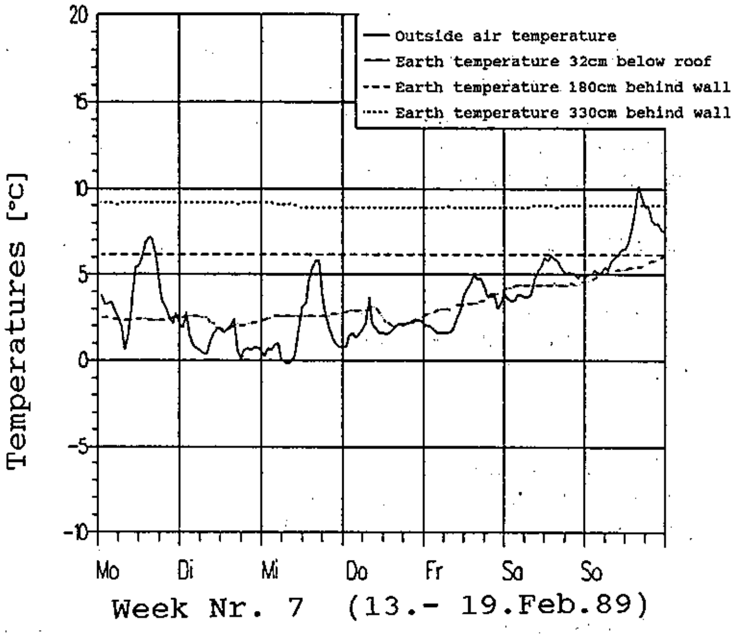
Each of the 70 channels were scanned at one-second intervals and hourly mean values transferred to a PC, where they were checked for errors and missing values. The data were analysed and processed graphically using standard spreadsheet software.

Influence of earth covering :

Figure 5 shows an example of hourly temperature measurements of the earth covering and outside air plotted over the period of a week. As may be seen, there is a considerable difference between the temperature of the earth covering on the roof, which approximates to the mean daily temperature, and that of the earth backfill against the walls, which remains substantially constant.

Figure 5:

Hourly mean temperatures at different locations in the earth cover and of the outside air



The difference in heat loss with and without earth covering may be seen by comparing the effective heating degree days. The earth covering reduces heating degree days of the roof by 8 percent whereas backfill reduces heating degree days of the north wall by 35 percent! Referred to the total heat loss of the building, this reduction amounts to 4 percent for the covering and 10 percent for the backfill.

In addition, earth covering has a positive effect on micro climate. Instead of a maximum of 60 °C measured under cement roof plates, the temperature in the earth covering rises to only 25°C.

Furthermore, simulations show that for winter and summer conditions, variation of the thickness of the earth cover between 25 cm (as built) and 80 cm has almost no effect on performance. This may be explained by the thickness of the insulation (18 cm), which is directly in contact with the roof. If an additional meter of earth were to be applied between roof and insulation, overheating problems in summer would be reduced.

Active and passive building performance :

During the heating season 87/88, the building was in "passive solar mode" only. During 88/89, combined passive and active operation (as designed) was initiated. Both heating seasons had approximately equal values for heating degree days (rather mild weather) and solar radiation. A comparison of the specific supplementary energy consumption (heating + electricity) shows:

Office building Haas + Partners (passive)	1987/1988	124 MJ/m²a
Office building Haas + Partners (active)	1988/1989	112 MJ/m²a

From this, two main conclusions may be drawn:

Employment of the window collector improves performance by only 10 percent over the already existing low figure in passive mode. The additional cost for the active system, amounting to sFr. 86,000.-, can thus hardly be justified by the gain in performance obtained. However, as will be seen later, there is substantial room for improvement of the active system.

Compared to other recently built high-performance buildings, this office building has a very low supplementary energy demand. Meteolabor (also included in Task XI) has air collectors but no earth covering, whereas Wald, which is a private home, has a sunspace over the whole south-facing facade and is earth covered.

Office building Haas + Partners	1988/1989	112	MJ/m²a
Office building Metorlabor	1988/1989	136	MJ/m²
Passive solar houses in Wald	1986/1987	246	MJ/m²

The total energy balance for Haas + Partners during a complete heating season (Oct. - Apr.) is approximately as follows:

GAINS	MJ/m²a	%	LOSSES	MJ/m²a	%
passive solar	60	30	windows	60	30
active solar	14	7	walls and roof	90	45
persons	16	8	air change	50	25
electricity	60	30			
heating	50	25			
total	200	100		200	100

The window collector (passive and active) with night-time insulation gains 14 MJ/m²a or 25 percent more than it loses and therefore has on average a negative heat loss coefficient!

Active collector efficiency can reach 50 percent (hourly maximum) with an average value of 39 percent over the heating season. This high value is also due to the fact that only the solar radiation during operation has to be taken into account. 20 percent of the energy gain reaches the room directly via the uninsulated air ducts. Rock bed performance is not very satisfactory because 50 percent of the energy delivered by the collector is lost (a) to the ground (even though the insulation is 20 cm thick) and (b) through back flow of air to the collectors at night, owing to the absence of flow restrictors. The other 50 percent are delivered directly to the room via 3 cm fiber wood insulation restrictors. This heat, together with that from the air ducts, can also lead to overheating and must therefore be regarded as lost.

In total, only 25 percent of the heat from the window collectors is effectively used. Following one three weeks' period with negligible active charging, the rock bed had released all its stored heat. This can be considered a good value and indicates that the storage capacity is sufficient. Furthermore, the presence of the active system serves to shorten the heating season of this particular building to a mere three months (Dec. - Feb.) as against five (Nov. - Mar.) when running in passive mode only.

Despite the relatively small energy saving of the active system, it has several worthwhile advantages in the context of comfort. Moreover, in Switzerland, it is not practical to work behind a south-facing window during periods of full sunshine in winter due to excessive glare and heat. Thus, even in the absence of an active system, some kind of semi-transparent shading device would be necessary.

Daily temperature fluctuations can be substantially reduced, as can be seen in figure 6. In active mode, these remain within a range of about 3 K during office hours, which is quite acceptable to the majority of occupants.

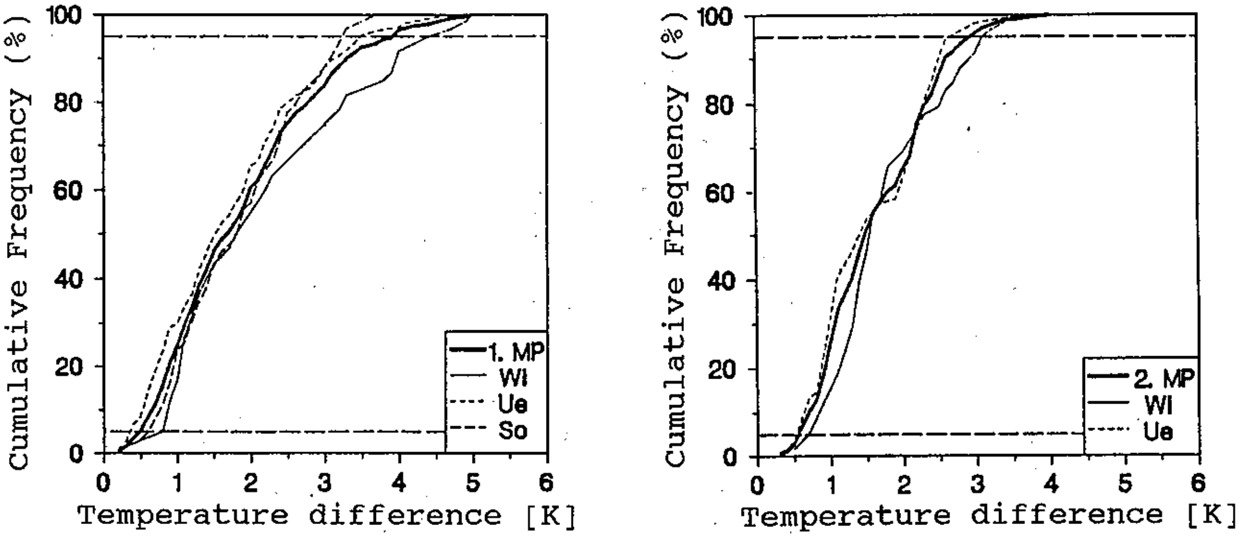


Figure 6: Frequency distribution of daily temperature fluctuations without active system (left) and with active system (right)

The improvement in temperature symmetry is even more marked. In passive mode, the large temperature difference experienced between the head and the feet when sitting behind a south-facing window can be most uncomfortable. Not so during active operation, where both window and floor (rock bed) are moderately warm. Thus the active system leads to a much smaller temperature difference, as can be seen in figure 7 (note the different scales on the x-axis).

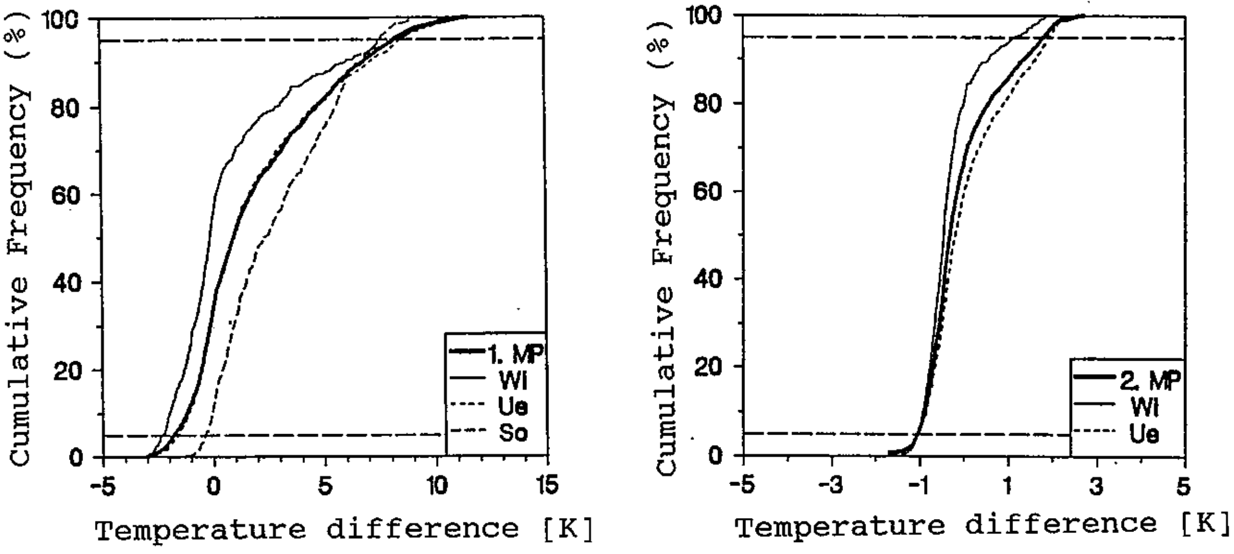


Figure 7: Frequency distribution of surface radiation asymmetry without active system (left) and with active system (right)

Computer simulations :

The simulations and parametric studies of the building in passive mode were carried out using SERIRES. Variations of the earth covering were discussed above. One other important issue is the use of the night-time insulation (NI), which turned out to be very effective as can be seen in figure 8.

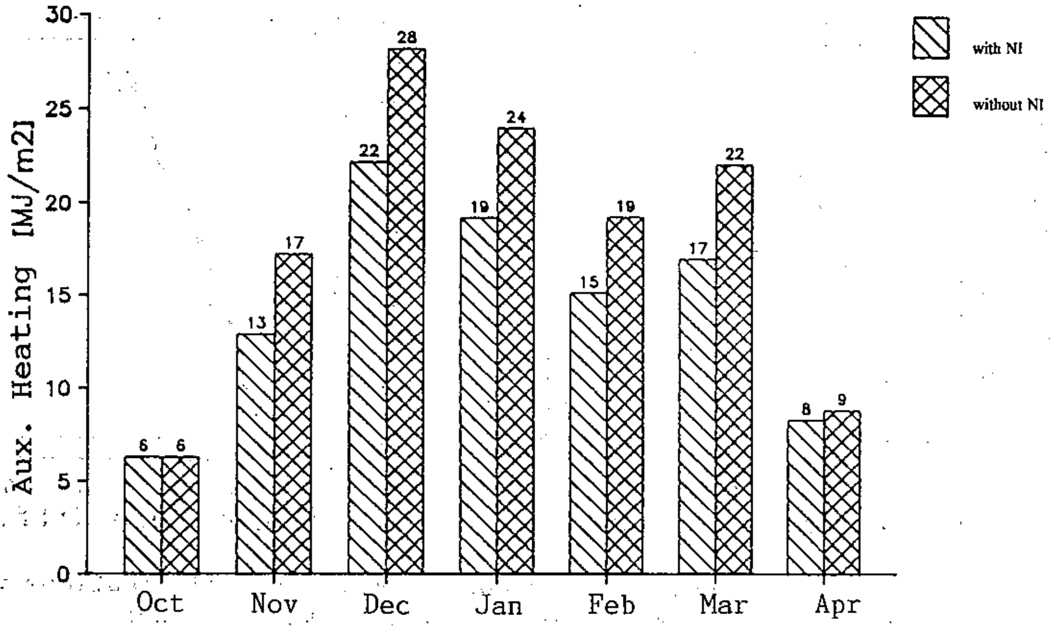


Figure 8: Influence of night-time insulation on supplementary heating demand

The reduction of the heat transfer coefficient of the windows from the already excellent value of 1.5 W/m² to 0.35 W/m² for at least half the total number of hours cuts down auxiliary energy need by 25 percent.

The other important parameter concerning energy consumption is the heating thermostat setpoint. 12 percent more energy is required per degree additional air temperature. Because of excellent insulation of all building surfaces and the radiant heating from the rock bed, an air temperature of 19 to 20 °C is sufficient.

Simulations under other climatic conditions showed that relative to the actual situation this building would use an equal amount of supplementary heating in Kopenhagen and 50 percent more in Oslo. In Rome, however, and also in Dallas, no additional heating at all is required. Indeed, in Rome, overheating would prove to be a severe problem.

Summer performance was also part of the simulations and different shading strategies to prevent overheating were investigated. Figure 9 shows an example of the results:

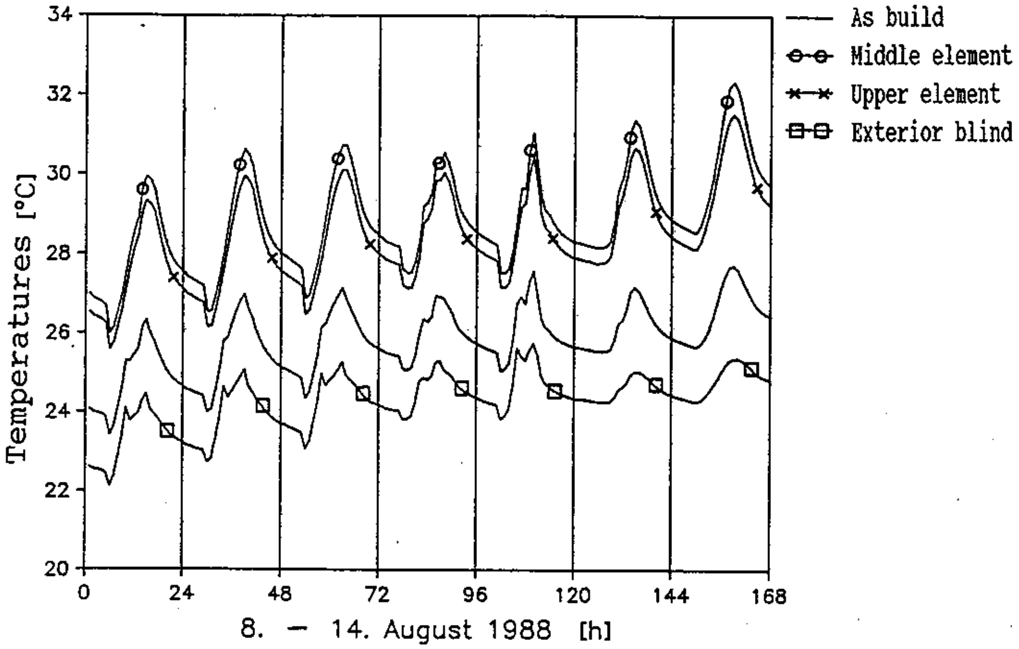


Figure 9: Temperatures during sunny weather in summer with different kinds of shading devices

The best solution providing the lowest inside air temperature proved to be an external movable shading device. Next in efficiency is the actual system installed, which has the white-coloured reverse side of the absorber shutters turned outwards. Here it would be possible to lower inside air temperature by 0.5 °C more if the collector were to be vented to the atmosphere. In August, when the weather can be very hot and sun angles are already low, fixed sunshades are not adequate.

The active system was simulated using a window collector module developed for the TRANSYS code as part of the Swiss contribution to IEA Task XI by Basler + Hofmann Engineers. A very close match to reality (measured data) was reached and serval parametric studies were done. Important results are:

- Installation of reverse-flow dampers would improve rock bed performance by 13 pecent. By beginning rock-bed charging in mid-September instead of mid-October a whole month of uncomfortable overheating conditions could be avoided.

- In the absence of other measures, insulation of the air ducts would lead to higher rock-bed temperatures but not reduce the overall energy required.

- Doubling the insulation of the rock bed against the room would increase rock-bed temperature and slightly decrease overheating of the working area but would not reduce overall energy required.

- Efforts to improve rock-bed performance invariably result in higher temperatures and thus automatically increase losses to the ground. It would therefore be an advantage to integrate (part of) the storage in the partition walls. Simulations showed that the time constant of such storage would be higher.

CONCLUSIONS :

The Haas + Partner office building has a very favourable energy balance. The earth backfill, together with the movable insulation at the windows, minimizes heat loss. As result of the solar and other features, the building requires only 15 percent of the heating energy of a conventional building, which is among the lowest in Switzerland.

The grass earth covering of the already highly insulated roof does not significatly improve the energy balance but has a significant effect on outside surface temperature and other micro-climatic factors.

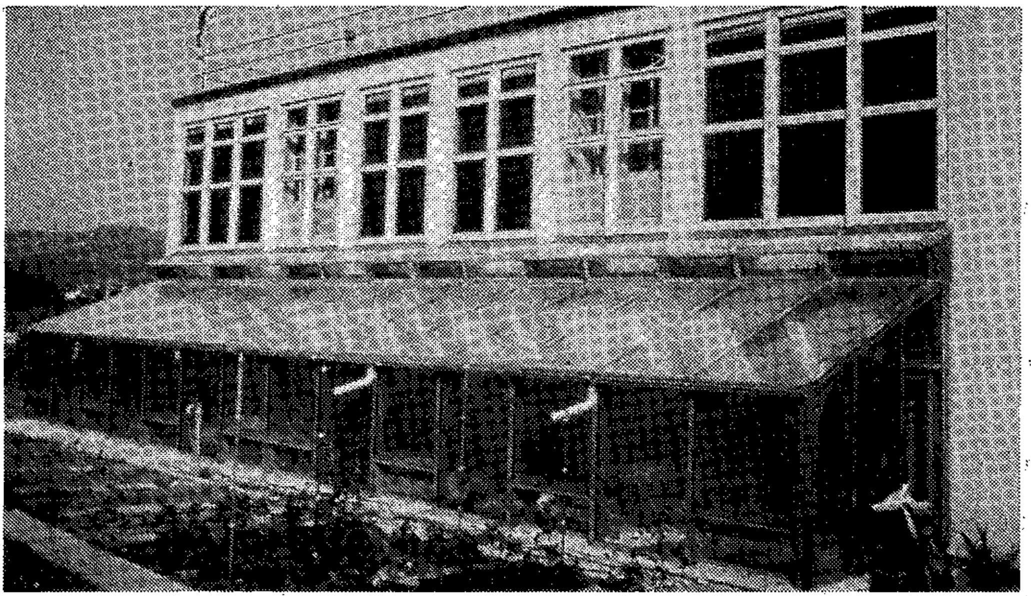
The building with its integrated control elements is very user-friendly. Natural light and natural ventilation can be adjusted individually in each office. The earth surround creates a perceptible and agreeable feeling of shelter and protection. The design requires occupants to participate in the seasonal and daily adjustment of the indoor climate of the building according to outside conditions.

The solar system, having but a single fan, operates entirely satisfactorily and the window collectors have a good coefficient of performance. The rock-bed storage can be further optimized by suppression of reverse air flow.

Reversed absorber shutters do not provide sufficient solar protection in summer. The best alternative would be a movable exterior shading device.

OFFICE BUILDING METEOLABOR INC.

GREENHOUSE AND COLLECTOR SOLAR AIR HEATING SYSTEM



ABSTRACT

Meteolabor Inc., an electronics firm in Wetzikon near Zürich, was committed to applying energy conserving techniques to its new multi-purpose building wing. The concept adopted was to use the building structure to store heat from a greenhouse and solar air collectors. An approximately constant indoor temperature of around 20 °C is achieved from October through April, thanks to the high thermal inertia of the building. The resulting thermal lag does, however, require occupants to adapt to seasonal conditions. The general tendency of the calculated values is confirmed by the experimental measurements.

INTRODUCTION

In 1973, Meteolabor Inc. moved into their first (conventional-style) building (Lab 1). Soon, more production space was needed, and the planning of "Lab 2" began in the early eighties. The new building was completed in 1985.

The building's energy concept stemmed from the owners' desire to apply the experience gained in the production of precise meteorological measuring instruments to their own building. In addition, the use of conventional technology, traditional craftsmanship and the simplest available energy-saving features were stipulated. Current monitoring, which is being undertaken by the owners themselves, includes data from the building's weather station. From the outset of Task XI, it was decided to make this object the subject of an advanced case study, as it seemed a promising application in a mixed industrial, office and domestic environment.

The measurements have been in progress since November 87. The aim of this study was:

- To test the efficiency of the two systems (temperature, humidity, performance, storage characteristics and electricity needed).
- To record building performance (resulting air temperatures).
- To propose possible optimisation strategies for future and more general applications of such systems.

BUILDING DESCRIPTION

Location :

The building, situated in the industrial zone of a small town, has other buildings adjacent to it on three sides. To the north-east it faces open country, from which direction cold and heavy winds are prevalent. The buildings to the south and west do not obscure the incidence of solar radiation.

Type :

The two-story building constitutes an extension to an older building and is of relatively compact construction. The whole of the south-facing facade is devoted to the active collection of solar energy, and consists of a greenhouse on the ground floor and air collectors and two direct-gain windows on the first floor. To the north, the building has a lean-to roof, and to the south, the roof is terraced.

Function :

The building is used mainly for the provision of supporting services, comprising stores in the cellar and workshops and a delivery department on the ground floor. The upper floor contains a meeting room, exhibition hall, photographic laboratory, reproduction room and measuring room. On the rooftop terrace, some of the meteorological data are collected. The building is occupied only intermittently.

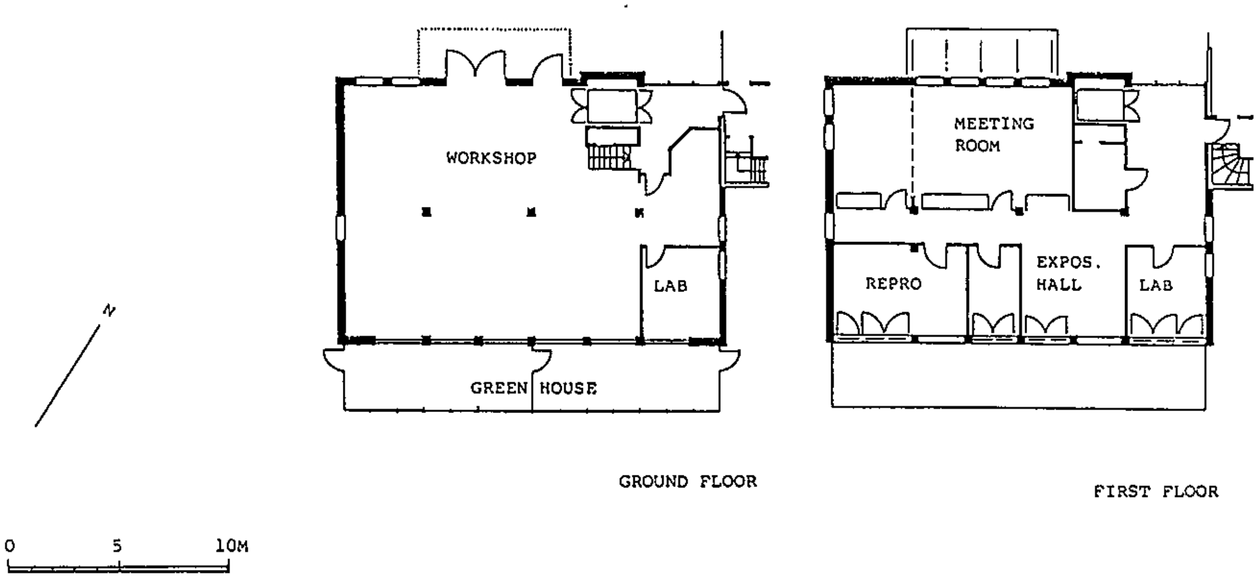


Figure 1: Floor plans and orientation

Construction :

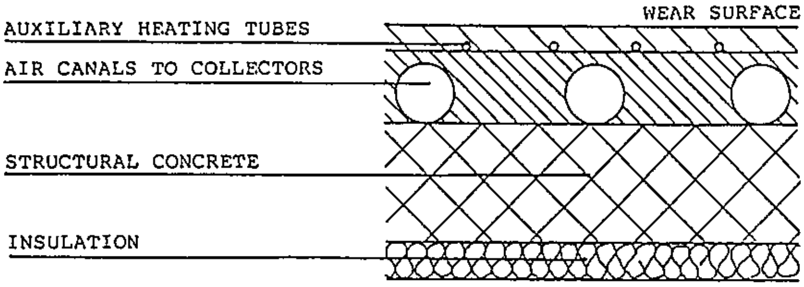
Particularly notable is the heavy construction of the building, with 25 cm thick masonry walls at the perimeter and reinforced concrete floors, as well as the high standard of insulation (12 cm thick). The roof is of wooden truss construction with planking. The service and personnel doors are of insulated sheet-steel. The greenhouse is a laminated wood framed construction with triple glazing in plexiglass. Specific heat losses are:

- Walls	0.3 W/m^2K
- Roof	0.2 W/m^2K
- Windows	1.9 W/m^2K

The overall building heat loss coefficient is only 320 W/K.

Services :

The rooms are provided with floor heating from solar heated air, which is fan-forced from the greenhouse and the collectors. The air is circulated through sheet metal tubes 15 cm ϕ embedded in the concrete. The system incorporates nine fans on the ground floor and six fans on the upper floor. Auxiliary heating is provided by a grid of copper tubes imbedded in the floor. Supplementary heat from an electric resistance heater and waste heat from a diesel generator is also available. However, this is used only occasionally, and then mostly at night.



Figur 2: Floor construction

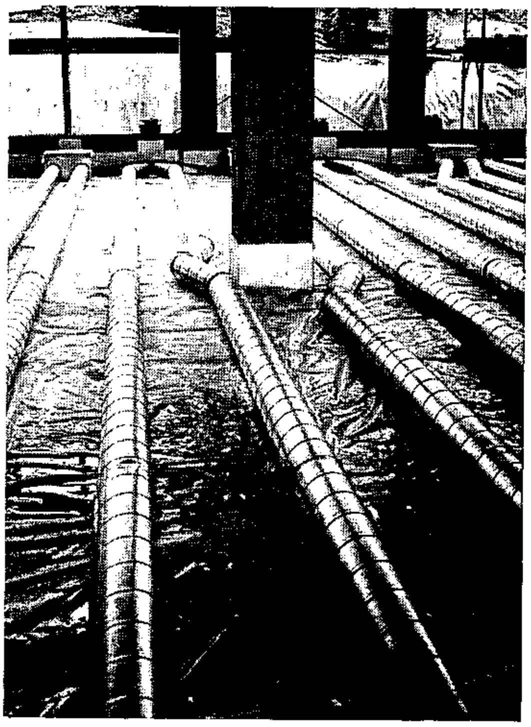
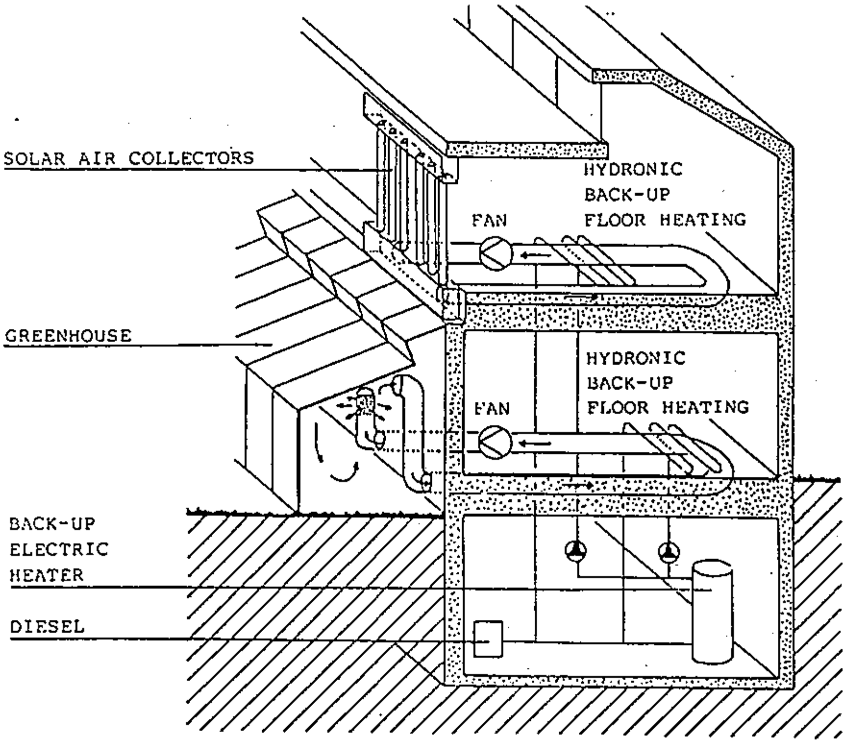


Figure 3: Arrangement of circulation ducts before casting concrete

Solar features :

Solar heated air is supplied from the greenhouse on the ground floor and by black metal tubes located at the back of wooden-framed, double-glazed panels on the upper floor. In summer, undesired irradiation is excluded from the collectors by reflecting roller blinds. To reduce overheating in the greenhouse, which has no sun shading devices, small windows may be opened manually or mechanically. The rooms are also cooled by natural ventilation. Though there is a minimum of glazing, the rooms nevertheless receive sufficient daylight. This is particularly true of the upper rooms, thanks to clerestory windows underneath the lean-to roof.



Greenhouse:	
Volume	126 m3
Floor area	50 m2
Glazing area	110 m2
Collector windows:	
Absorber volume	1.5 m3
Glazing area	27 m2
Storage:	
Volume	317 m3
Thermal mass	752.4 MJ/K

Figure 4: Cross section showing the energy system

System control :

All control functions (solar and auxiliary) are integrated into the meteorological data-acquisition system (see chapter on measurements):

- Ventilation for air collectors and greenhouse by temperature difference.

- Auxiliary heating is supplied to the building using a sophisticated optimization algorithm, which allows outside and inside air temperatures to be forecast for the next two days using existing building parameters and the weather pattern of the previous few days.

- The air collector blinds are automatically closed when temperatures in the concrete floor rise above 25°C. The fans are also switched off. As an additional insulation measure at night, the blinds are closed when temperatures fall below +5°C.

- Alarm functions are provided for collector and greenhouse overheat and for greenhouse freezing (danger to plants).

MEASUREMENTS

Objectives and methods :

The investigations were planned with the following objectives:

- To test the efficiency of the two systems (temperature, humidity, performance, storage characteristics and electricity needed).
- To record building performance (resulting air temperatures).
- To propose possible optimization strategies for future and more general applications of such systems.

The data obtained in the course of this study are of particular interest, not least in view of the owners' own professional involvement in the project. The owners, METEOLABOR, run their own automatic weather station to test and demonstrate their products. The data recording unit, KLIMET, collects all the energy-relevant data and controls the auxiliary equipment (fans, auxiliary heating, blinds etc.). Measurements were made of:

Climate:	- Air temperature and humidity - Wind speed and direction - Global insolation in 6 main directions - Earth temperature (5 and 50 cm below surface)
Greenhouse:	- Air temperature (1 m above ground) - Earth temperature (5 cm below surface) - Inlet and outlet air temperatures of the ventilation system
Collector:	- Surface temperatures (at various points) - Inlet and outlet air temperatures of the ventilation system
Building:	- Air temperatures on each floor - Floor temperatures on each floor

Temperatures were measured using high-precision thermocouples of the owners' manufacture. Because very thin wires were used, measurements of air temperature (e.g. in the greenhouse) are subject to negligible irradiation error.

Data map :

All data are stored at 10 minute intervals. The data logger (KLIMET) uses a 16 bit A/D converter; the recording accuracy is ±0.1 °C. For this report the necessary data were stored and analysed using DBASE and compatible software products and integrated to obtain hourly values.

Experiments :

The experiments undertaken aimed mainly at an optimization of the air circulation from the solar source (collectors and greenhouse) to the storage (concrete floors).

The fans (9 for the greenhouse, 6 for the collectors) have two operating speeds labeled 80/40 watts. In the experiments, power input was lowered in stages and the resulting air speed in the ventilation ducts measured (figure 5).

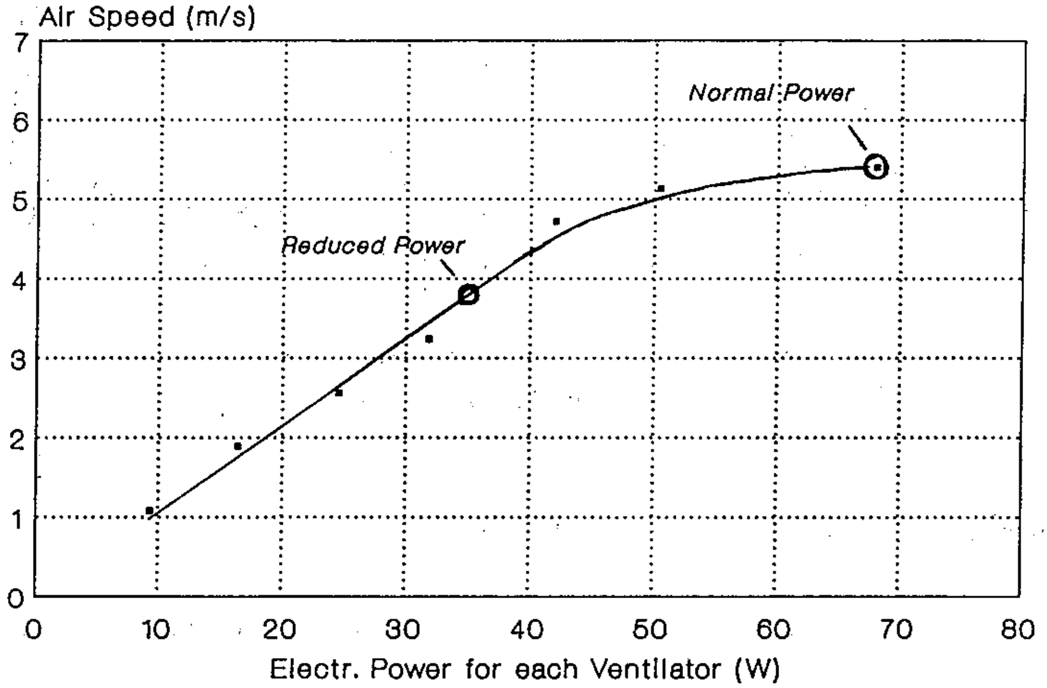


Figure 5: Ventilating power versus air speed achieved

Probably due to motor characteristics, the air speed levels-out at higher values of power input. In these circumstances, it would be more economic to run the fans at about 50 watts.

The main improvement would be to use greater diameter ducts for the floor, resulting in lower resistance and thus lower ventilation power. In this particular case, however, this was not considered feasible owing to possible static-strength problems with pipes integrated directly within the bearing structure of the reinforced concrete floor.

Nevertheless the present system works at 93 percent efficiency, which means that only 7 percent of the heat has to be added externally in the form of electricity for the fan motors.

Performance of greenhouse and air collectors :

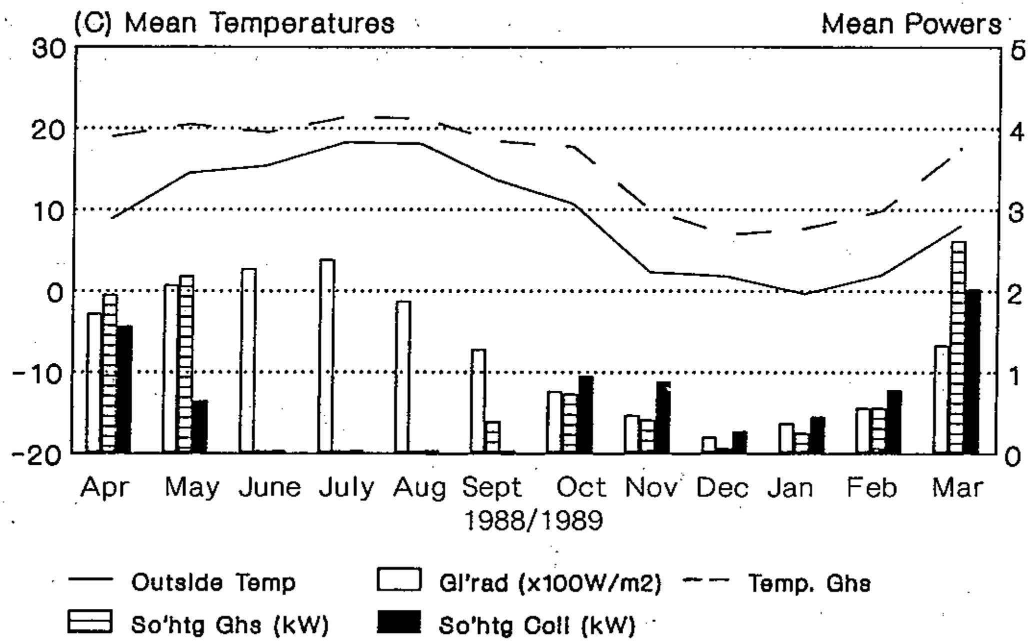


Figure 6: Energy input and mean temperatures

Figure 6 shows monthly mean values to compare greenhouse and air collector performance. The following conclusions can be drawn:

- The vertical air collectors contribute most energy to the building between October and February when sun incidence angles are low. The worse the weather (i.e. low insolation, low temperatures), the more efficient is the collector. The collectors work with a mean efficiency over the heating season of 55 percent, delivering a total of 5500 kWh heat.

- The efficiency of the greenhouse is highest in spring (March, April, May), when energy demand is high and sun incidence angles are high (the greenhouse roof is tilted at 30° to the horizontal). In winter, the low insolation is mostly sufficient to pevent freezing in the greenhouse, but only very little excess heat can be transferred to the building. Mean efficency over the active heating season is only 16 percent, which may appear low in comparison to the air collector. However, bearing in mind that the heating air is merely a by-product of the greenhouse, whose primary function is to heat itself and provide a buffer zone against heat loss from the building, the figure of 16 percent, amounting to 6500 kWh, is quite remarkable.

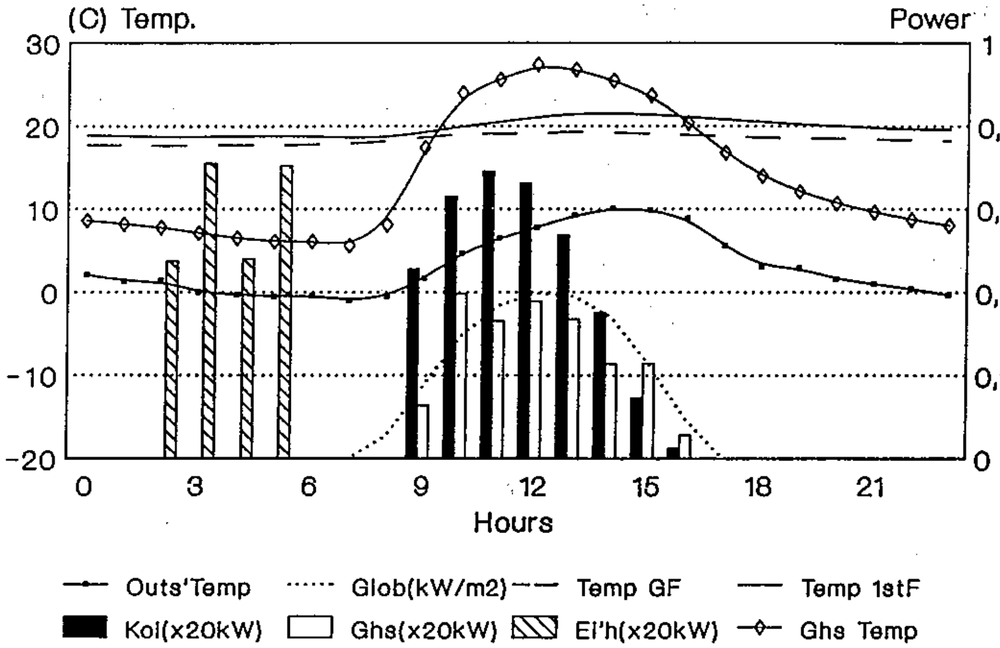


Figure 7: Temperatures and energy input on a clear winter's day.

The reaction of the building to changes in climatic conditions is well illustrated in the case of a clear winter's day (figure 7). Starting at midnight, outside air and greenhouse temperatures may be seen to drop steadily to -1 and +7 °C respectively. Between 2 and 5 o'clock, auxiliary heating is applied to the concrete slabs to prevent the inside temperature dropping below 18 °C. After sunrise, the temperature in the collector rises more quickly (low mass) and to higher values than in the greenhouse. At 9 o'clock, three times more energy is supplied by the collectors than by the greenhouse. The higher temperatures of the first floor are also due in part to the higher passive gain. Since the vertical collectors are more sensitive to the sun's position, and in view of the higher 1st floor temperatures (23°C), their energy output declines more quickly than that of the greenhouse. The latter also profits in the afternoon from its (albeit small) storage capacity.

Whereas for the ground floor (greenhouse) it is obviously necessary to provide supplementary heating at night, this proceedure is questionable for the first floor for the following reasons:

- Active and passive gains are much higher.
- Floor heating lowers the efficiency of the passive (and in this case also of the active) heating.

This leads to the following hypothesis which should be taken into account for future investigations:

- If the following (winter's) day is forecasted to be sunny, auxiliary heating should be switched to "ground floor heating only".

CONCLUSIONS AND RECOMMENDATIONS

- 60 percent of the total energy demand of the building is covered by the sun (active and passive). Owing to the well-conceived insulation strategy, the supplementary heat input amounts to only 120 MJ/m^2 per year.

- Floor heating and floor storage proved to work satisfactorily and were shown to maintain an acceptable comfort level. The following improvements should be considered in future applications:

    - Larger diameter heating ducts integrated into the bearing structure of the floors.

    - Optimization of auxiliary heat input using weather forecasting techniques. This topic has recently been the subject of much debate, and could lead ultimately in conjunction with the advent of digitised communication (INDS: "Heating and Cooling Control by Digitised Weather Forecast") to the initiation of a new IEA Task.

- Air collectors work satisfactorily. Possible improvements are:

    - Multi-layer plexiglass instead of insulating glass would be lower priced, have better heat resistance and produce higher light defraction, leading to more evenly heated absorbing tubes.

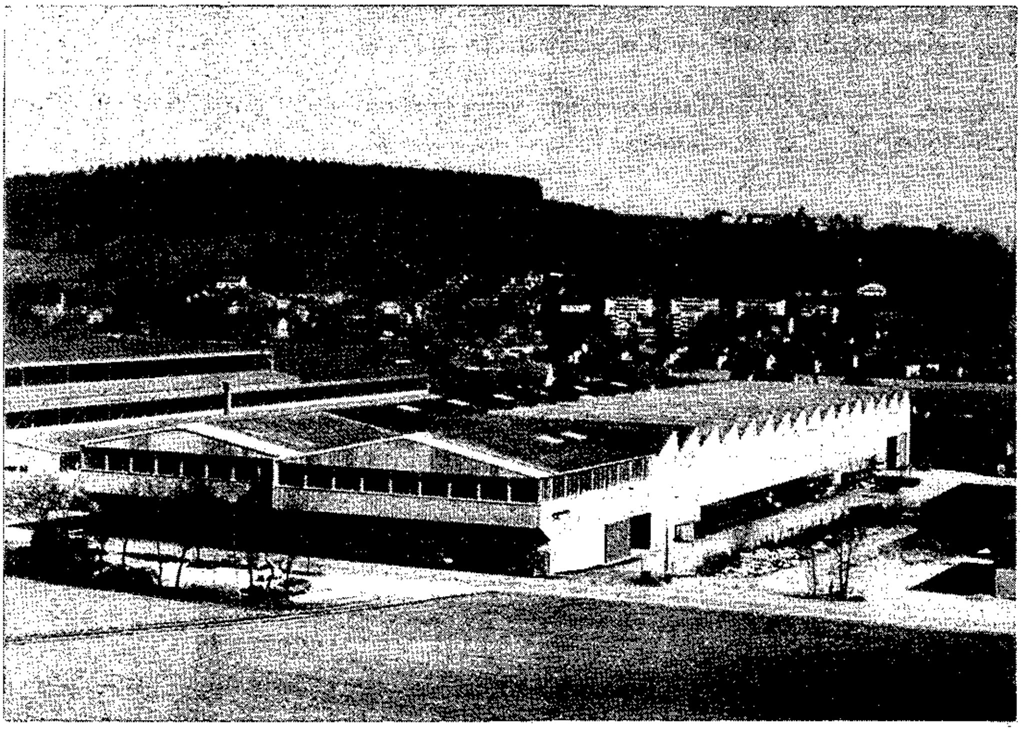
    - The use of aluminium ducts would give more even heat distribution and better heat transfer.

- The greenhouse can be considered as a good compromise, despite the fact that the active energy input to the building during the cold winter months is small. The ventilation capacity of 5800 m3/h (or 24 air changes per hour) proved to be a good value. Taken in conjunction with the results of other studies, the following general recommendation may be made:

    - The ventilation capacity of a sunspace or greenhouse used for heating purposes should be designed for approximately 20 air changes an hour.

- This essentially simple and easily understood heating system requires the occupants to adapt themselves to the prevailing seasonal conditions. Provided suitable clothing is worn, the majority of occupants find room temperatures, which are in the range of 18 °C to 24 °C, to be quite acceptable (differences of temperature from one day to the next and from room to room do not exceed 1 K).

STEEL WAREHOUSE KÄGI
SOLAR ATTIC AIR HEATING SYSTEM



ABSTRACT

The steel warehouse of the Kägi company in Winterthur near Zürich consists of two attached warehouse halls. The older hall to the left is completely uninsulated and has an open basement to store infrequently used items. To prevent condensation of air on the cold steel surfaces in spring and early summer and to obtain a smaller temperature difference (hall - basement) for workers in summer (productivity loss due to illness) as well as to raise temperatures in winter, a ventilation system was installed to circulate sun-warmed air from under the roof to the basement. It was possible to demonstrate that such a system works well and cost effectively compared to a conventional heating system.

INTRODUCTION

In 1986 the owner of the warehouse conceived the idea - as an alternative to a conventional heating system - of installing an air collector system to transport solar-heated air from under the roof to the cold basement. It was decided to make this object the subject of an advanced case study for IEA Task XI because of its anticipated low cost and its application in an industrial environment.

The measurements, which have been in progress since November 88, continued until March 90. A second winter period became necessary because the control system of the air collector did not function as intended.

The aim of this advanced case study was:

- To test the efficiency of the system (temperature, humidity, performance, storage characteristics and electricity needed).
- To propose possible optimization strategies for future and more general applications of such systems.

BUILDING DESCRIPTION

Location :

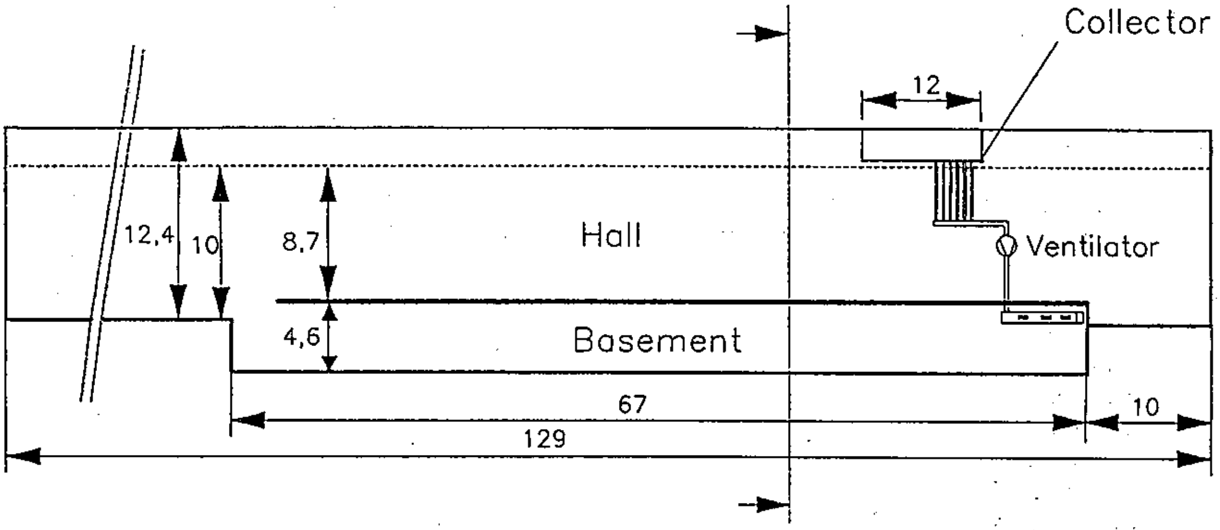
The building is situated in a small industrial area on the outskirts of the city of Winterthur, which lies about 20 km north of Zürich. There is no major solar occlusion. The photograph on the front page shows the two adjoining warehouse halls as viewed approximately from the south in February.

Type :

The complex consists of two connected halls (2 x 2500 m^2). The "old hall" (at the left on the photograph) was constructed in 1961 and the "new hall" (to the right) in 1968. The building sections visible in the foreground (about one third of both halls) were added between 1982 and 1986 for additional storage capacity. The basement with its heavy concrete foundation and ceiling was inserted beneath the old hall in 1984. Both halls are about equal in size. The principal dimensions of the old hall are given in figure 2. The roof surfaces have a 20 degree slope, orientated towards the south-east and north-west.

Function :

The primary function of the building is the storage of steel pipes. The northern part of the old hall was always closed and moderately heated and also had a small office section, a coffee-room and dressing rooms for the employees. All other storage areas were originally open to the ambient. Severe problems with extreme temperature differences and condensation, particularly in the new basement, occurred. In 1986 the halls were closed in, automatic doors for the trucks were installed and the ventilation system to transport sun-warmed air to the basement was added.



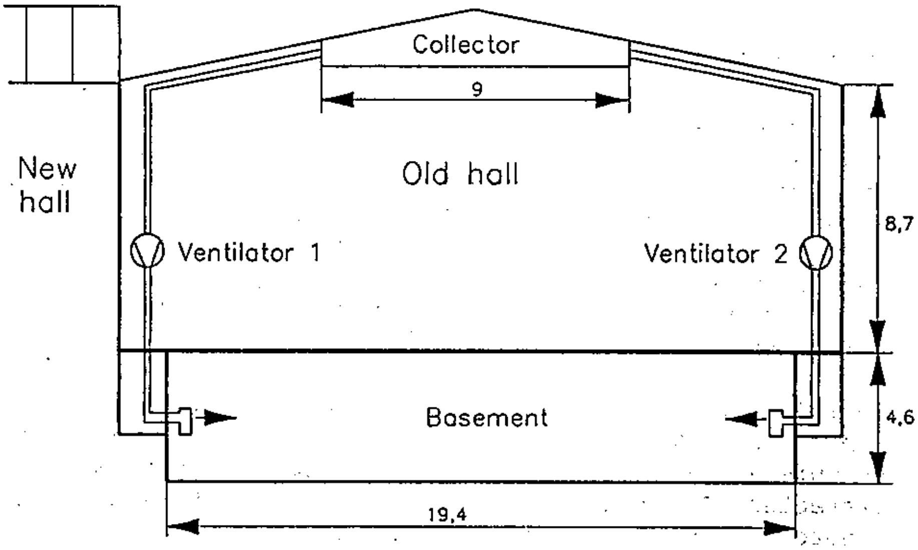


Figure 1:

Cross sections through the warehouse hall

Construction :

Both halls are of lightweight, steel-frame construction built on a 3 m thick lime, sand and brick foundation. The upper part is made of corrugated fiber panels with a band of single glazed windows (glass or polycarbonate). The roof consists of corrugated fiber boards with skylights. Only the saw-tooth roof of the new hall and the south-facing walls are insulated with rock wool (5 cm).

Even considering the many tons of steel pipes stored within, the above-ground halls with their huge volume of 2 x 30'000 m3 must be regarded as being of extremely light construction.

The basement, however, is of very heavy concrete construction with the following characteristics:

Volume:	6'700 m3
Surface:	3'300 m^2
Mass:	2'800 tons
Stored steel:	500 tons
Heat capacity:	930 kWh/K

The storage capacity of nearly 1 MWh/K is unusually high.

Services :

Moderate temperatures (around 16 °C) are maintained in the new hall (in the section under the saw-tooth roof) during the winter period by oil-fired air heaters. The old hall has no heating system other than the "air collector". Here, the temperature approximately follows the daily and seasonal fluctuations in the outside temperature. In summer, however, temperatures can rise above ambient because the thin, dark, uninsulated roof acts both as a collector and as a radiative heat source. At night and in winter the roof loses heat to the environment by radiation. The cool air underneath the roof then flows downwards and forms a layer of cold air in the (open) basement, with temperatures dropping to near zero. In a normal (closed) basement they would stay much closer to the soil temperature (about 5 °C).

Solar features :

Due to natural temperature stratification and low air change rates in the basement, temperatures remain below 10 °C until spring and early summer. Because the moisture content of the air is considerably higher in spring and summer than in winter, frequent condensation on the cold steel surfaces occurred, causing degradation of the stored material. Furthermore, the employees who normally wear clothes appropriate to the warm environment in the hall (with temperatures around 30 °C), frequently became ill with colds when working in the cold and damp conditions in the basement.

To solve this problem, a simple open-loop ventilation system was installed to supply sun-warmed air (9'400 m3/h) from under the roof to the basement (figure 1). Figure 2 shows the air collector from which the sun-warmed air is extracted. It consists of a very light ceiling made of 5 cm rock-wool panels. Figure 3 shows a picture taken from the entrance of the basement towards the rear, where the air outlets can be seen.

The goal of this installation was to

- Prevent extremely low temperatures in winter
- Prevent extreme temperature differences (hall to basement) in spring and summer
- Prevent condensation on steel surfaces
- Prevent loss of productivity due to illness.

The system is regulated electronically using two control values:

- Air temperature difference between collector and basement
- Relative humidity of the collector air

In the original system, it was intended that when the temperature difference exceeded 10 °C and relative humidity was below 40 percent, the two fans be turned on.

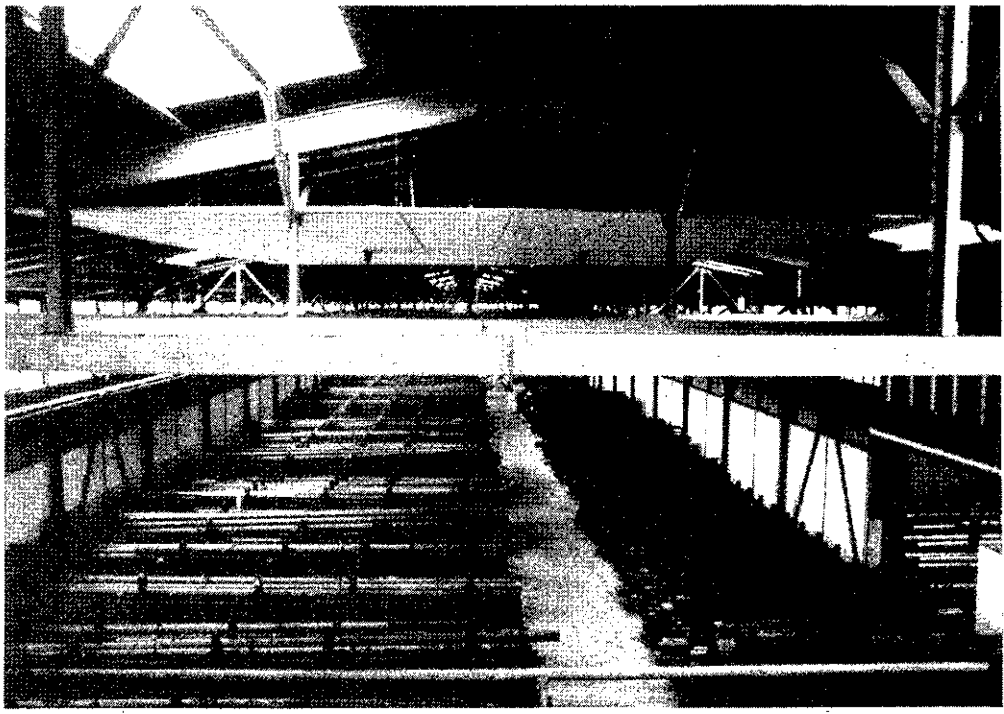


Figure 2: The collector attached under the roof over the warehouse hall containing the stored steel pipes.

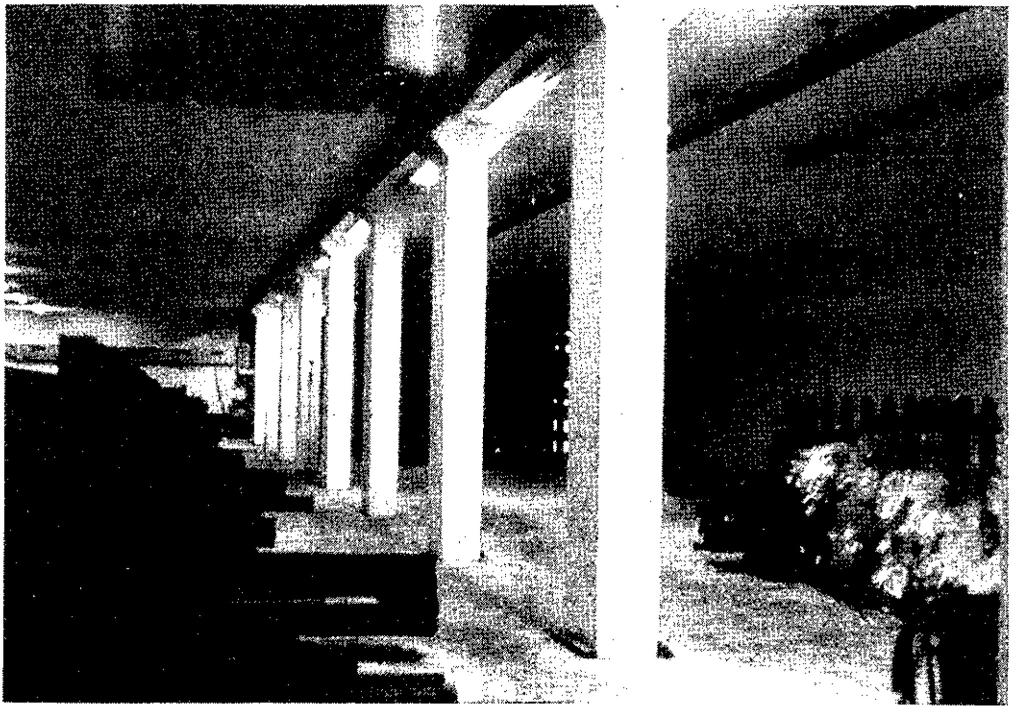


Figure 3: The open basement under the warehouse hall. In the background, one of the air outlets can be seen.

MEASUREMENTS

Objectives and methods :

The measurements were planned with two objectives:

- To test the efficiency of the system (temperature, humidity, performance, storage characteristics and electricity needed)
- To propose future optimization strategies and identify future and more general applications for such a system.

To this end, it was necessary to clarify the thermo-hydraulic interactions between hall, basement and the ambient.

Accordingly, 21 points were measured at hourly intervals:

Climate:
- Global horizontal insolation.
- Ambient air temperature.

Hall:
- Temperature and relative humidity within the collector.
- Temperature below the collector in the working area.
- Temperature under the roof at a distance from the collector and in the working area (to determine temperature stratification and establish whether the ceiling under the collector could have been omitted).

Basement:
- Basement temperatures at three different levels
- Temperature near the ceiling at the exit of the basement to the hall
- Relative humidity of basement air.

Storage:
- Temperature of the foundations (8 cm below floor).
- Temperatures of the 45 cm thick concrete ceiling (one at 8 cm above ceiling level and one at 8 cm below floor level of the hall).

System:
- Run time of fans.

Temperatures were measured by thermocouples with the exception of the combined temperature/humidity sensors (Pt 100). The volumetric flow of the fans was measured on two occasions on site with a hand held anemometer. Data were recorded on a KAY DIGI LINK data logger with a scan rate of eight channels per second. Hourly mean as well as maximum and minimum values were transferred to a tape recorder. The data logger uses a 16 bit A/D converter; the recording accuracy is +/- 0.1 °C and +/- 1 percent for relative humidity. The data were then transferred to an IBM-compatible PC where they were stored and processed using LOTUS 1-2-3 spreadsheet and compatible graphics software.

Project Kägi

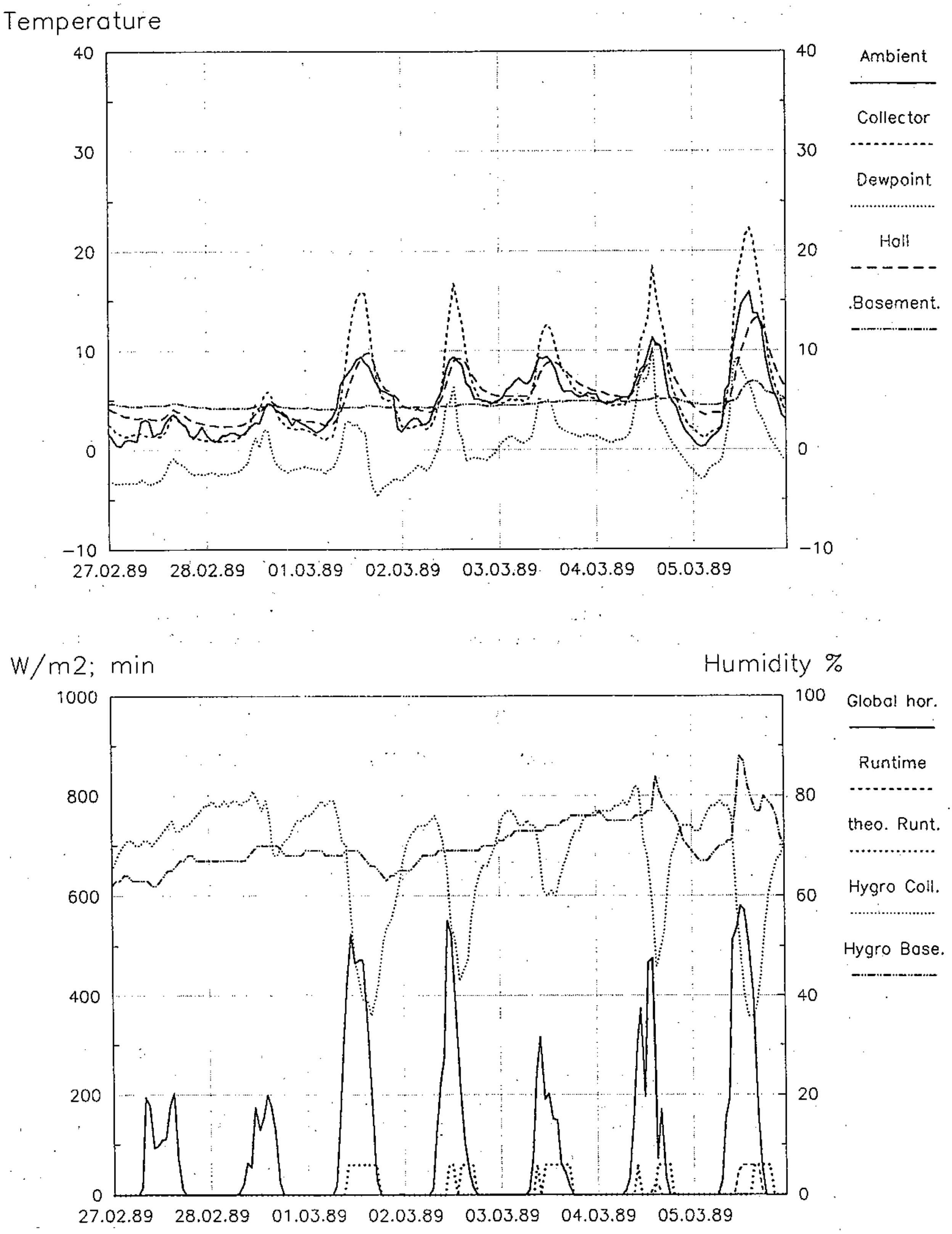


Figure 4: Measured hourly values of temperature, insolation, runtime and humidity in winter

Experiments :

Tests to verify the control system were required from the outset for two reasons:

1). Despite excellent weather conditions, the fans did not start.

2) It seemed questionable whether the relative humidity of the collector air would be a viable control value for the purpose of preventing the transfer of excessively humid air to the basement.

After performing a system check, the supplier of the control equipment discovered a 10 percent negative shift of the setpoint for relative humidity so that it switched at 30 instead of 40 percent. This effectively put the fans out of action, since it is rarely that dry! The value was adjusted to 70 percent.

Furthermore, the temperature setpoint (DT = 10 K) apparently suffered from positive drift. The setpoint was thus adjusted to DT = 5 K, but during the following weeks the system commenced operation only at temperature differences above 10 to 11 K. Thus the temperature drift must have been of the order of 6 K!. In view of this uncertainty, it was decided to control the fans using the data logger.

To prevent condensation in the basement, the dewpoint of the incoming air must be below basement temperature. The dewpoint depends on the absolute water vapour content of the incoming air and not on relative humidity. The dewpoint itself (TD) can either be measured directly or calculated using the temperature (TA) and the relative humidity (FA) of the air as follows:

$$TD = \frac{238.4 * \{\ln(\%F_A) - 4.6052\} * \{T_A + 238.3\} + 4115.2 * T_A}{4115.2 - \{\ln(\%F_A) - 4.6052\} * \{T_A + 238.3)}$$

From this formula, it is obvious that air temperature (TA) is the dominating factor in determining the dewpoint. In consequence, this formula was programmed into the data logger. This controlled the fans from April 89 onwards using the following setpoints:

$$T_{collector} - T_{basement} > 3\ °C$$

$$T_{basement} - T_{dewpoint} > 0\ °C$$

To determine how many hours of ventilation were lost using the previous system during the winter 88/89, the formula was programmed on a PC and a dewpoint and a "theoretical runtime" were calculated. The problem is well illustrated by figure 4. The last two days in February were too cold for the system to start. On March 1, it was sunny and the DT collector-basement rose to 10 K, but the system still did not start. Theoretically, and assuming the temperature set points given above, it would have run eight hours, because the dewpoint was at no time critical. On the 5th of March, DT increased to 15 K. Here, the control system switched on, even though the dewpoint was critical. The new control strategy would have handled this situation correctly (see "theoretical runtime" in figure 4 below).

Project Kägi

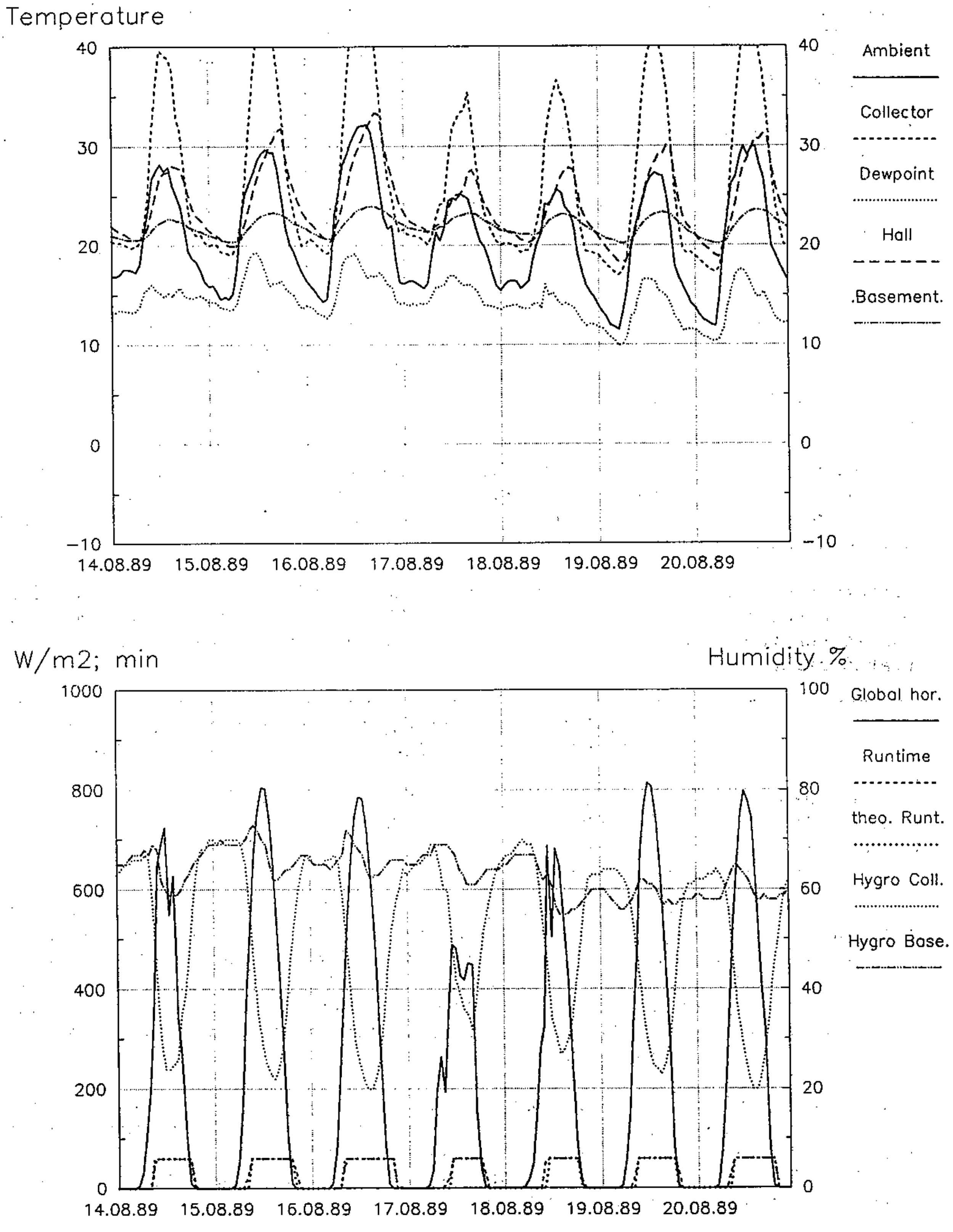


Figure 5: Measured hourly values of temperature, insolation, runtime and humidity in summer

Long-term Performance :

Relative humidity under the roof ("Hygro Coll.") reaches a maximum in December (77 percent mean) and is lowest in June (46 percent). This behaviour is typical for outdoor climate. On the other hand, outside temperatures and dewpoints are low in January and peak in July. Figure 6 shows clearly that the dewpoint pattern closely follows that of the outside air temperature. Monthly mean values of relative humidity, outside air temperature and dewpoint were also plotted.

The variation of mean relative humidity in the basement follows that under the roof but with a smaller amplitude.

One of the most interesting periods is March to April 89. Although both months have approximately the same mean outside air temperature and global insolation, due to increasing energy transfer to the basement mean temperatures there as well as in the hall and in the storage mass (concrete ceiling and foundation) rise steadily. Especially in April, the temperature of the hall is substantially raised by the heat from the concrete basement ceiling, whose temperature closely follows mean basement temperature. Therefore it can be concluded that the system is able to "floor-heat" the hall, and thus has a positive effect not only on the the working area in the latter, but also on the basement.

In summer (July, August), mean basement temperatures are around 21°C, whereas temperatures in an unheated basement of this size would not rise above 16°C at the most, leading to a high risk of condensation. In figure 5, a week's period in summer is shown.

Performance reaches a peak in June, when 10 MWh of heat are transferred, boosting basement temperature from 15 to 20 C. Over a whole year, performance varies substantially. Performance can be divided into three periods as illustrated below:

	global hor/Mt [kWh/m²]	energy/Mt [kWh]	runtime/Mt [h]	performance [kW]
Nov - Jan	25	600	50	12
Feb / Oct	50	2000	100	20
Mar - Sep	150	7000	250	30

The fans are rated at 2 kW. Running the system from November until January is not very efficient, since insolation is generally poor, the north-west roof receiving no sun at all. Under the present collector setup, the small amount of energy collected under the south-east roof is effectively lost to the north-west roof. In February (and October), the situation improves somewhat and from March to September, when the sun impinges strongly on the north-west roof, performance is excellent.

Comparisons showed that the temperatures within the collector construction and under the open roof were practically the same. This collector construction is therefore of no particular advantage. It does, however, restrict the downward flow of cold air at night and shields infrared radiation from the working area during strong sunshine .

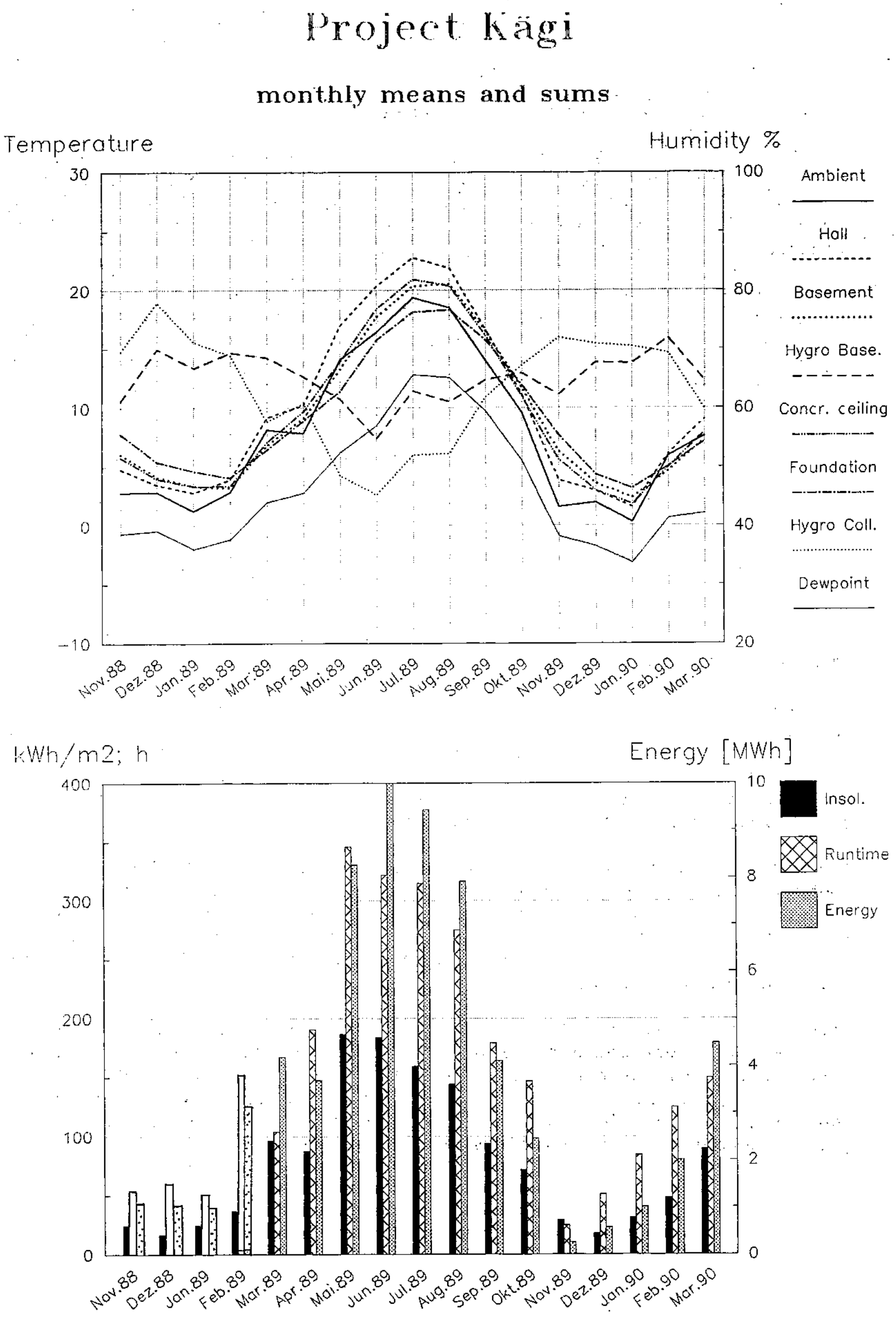


Figure 6: Performance overview. Runtime and energy figures of the first four month are theoretical.

Analysis of dewpoint critical conditions :

An analysis was carried out to determine how important it is to prevent the circulation of low dewpoint air to the basement for the whole of the year. In figure 7, the monthly and the overall frequency distribution of dewpoint undershoot below basement air temperature is shown. Some of the possible interpretations are:

- 70 percent of all hours with temperatures below the dewpoint have an undershoot smaller than 3 K. The period from November to January falls completely within that range. Although this would not cause direct condensation, the relative humidity would be high enough to increase the corrosion rate.

- The most critical months for dewpoint undershoot are February to April, because basement temperatures are still low following the winter period.

- June to August are not critical, since the the basement is warm.

Also of interest is the relative humidity during supposedly critical periods. Figure 8 shows the respective monthly and overall distribution. It is obvious that: All classes of humidity are represented for a significant proportion of the total time. In winter, somewhat higher values (50 - 90 percent) prevail, in summer somewhat lower (10 - 50 percent).

With the present control system, it was found that even after careful adjustment of the set points to prevent condensation with the system in operation, about 10 percent of operating hours - mainly from October to March - tend to be critical. (The maximum relative humidity that can be tolerated for a certain temperature difference between outside air and basement can for example be obtained from the Mollier h-x diagram.)

The question arises whether it is worthwhile to use relative humidity as a control criterion at all if it does not prevent condensation. Would it not be sufficient simply to rely on temperature difference, which would be simpler and less expensive? This has to be negated, because, as the measurements show, the proportion of the total hours during which critical conditions can occur can easily double.

With present settings, the fans will only operate from February to October. To permit all-year-round operation, the settings would have to be altered to a temperature difference of 6 K and relative humidity below 70 percent. However, any particular choice of set points represents a compromise between operating time and freedom from condensation. A solution would be to use a genuine dewpoint based control system.

Klasse	Nov. 88	Dez. 88	Jan. 89	Feb. 89	Mar. 89	Apr. 89	Mai 89	Sep. 89	Okt. 89	Dez. 89	Feb. 90	Mar. 90
>10	0	0	0	0	0	0	0	0	0	0	0	0
9-10	0	0	0	0	0	0	0	0	0	0	2	0
8-9	0	0	0	0	0	0	0	0	0	0	4	0
7-8	0	0	0	0	0	0	0	0	0	0	3	0
6-7	0	0	0	0	1	0	0	0	2	0	4	0
5-6	0	0	0	1	2	2	0	0	1	0	7	3
4-5	0	0	0	0	1	1	0	2	6	2	7	1
3-4	1	0	0	2	7	1	1	2	5	0	6	0
2-3	3	0	0	7	12	4	5	2	5	16	9	3
1-2	2	1	3	10	13	4	5	3	3	17	7	8
0-1	11	11	3	18	17	1	10	3	6	13	5	5
Total	17	12	6	38	53	13	21	12	28	48	54	20

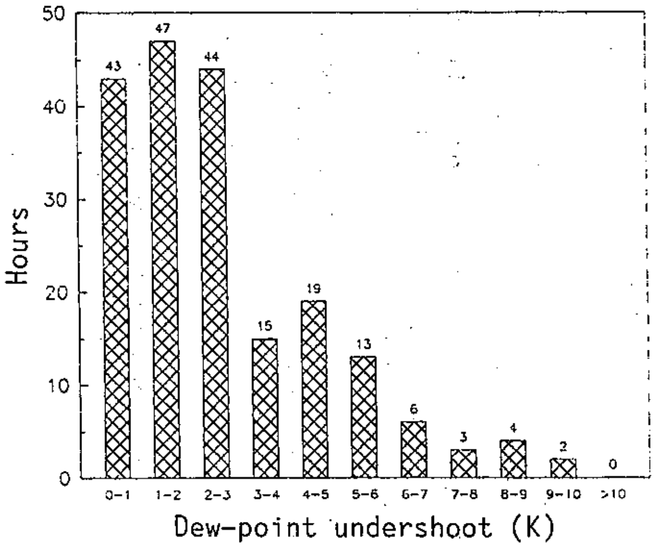


Figure 7: Monthly and overall (Apr. 89 - Mar. 90) distribution of hours were dewpoint falls below basement temperature

Klasse	Nov. 88	Dez. 88	Jan. 89	Feb. 89	Mar. 89	Apr. 89	Mai 89	Sep. 89	Okt. 89	Dez. 89	Feb. 90	Mar. 90
0-10	0	0	0	0	0	0	0	0	0	0	0	0
10-20	0	0	0	0	0	0	4	0	0	0	0	0
20-30	0	0	0	0	10	8	9	2	0	0	0	4
30-40	0	0	0	0	16	4	4	4	1	0	4	4
40-50	0	0	0	1	9	1	2	3	13	0	16	2
50-60	4	0	0	7	8	0	1	2	9	2	13	5
60-70	3	2	1	5	5	0	0	1	3	3	12	3
70-80	4	1	3	23	4	0	0	0	1	10	4	2
80-90	6	9	2	2	1	0	0	0	1	33	5	0
90-100	0	0	0	0	0	0	0	0	0	0	0	0
Total	17	12	6	38	53	13	20	12	28	48	54	20

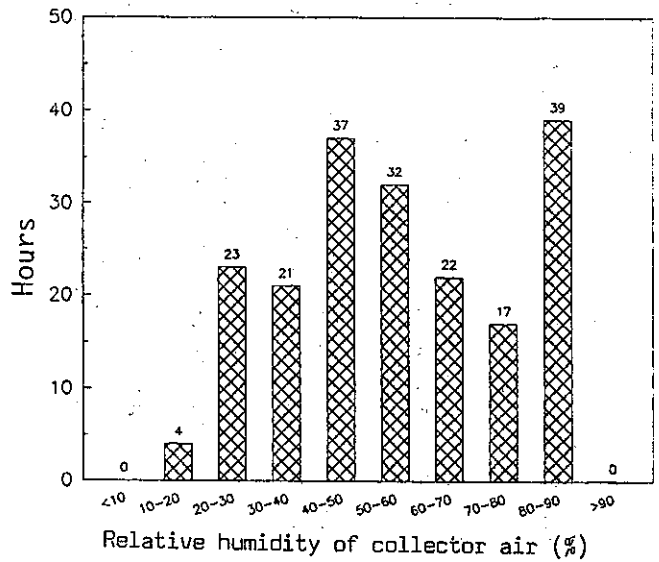


Figure 8: Monthly and overall (Apr. 89 - Mar. 90) distribution of relative humidity within the above hours

CONCLUSIONS AND RECOMMENDATIONS

It is more cost effective to simply extract the air from under the roof without an additional ceiling. Generally speaking, temperature stratification is as good as with an insulated collector construction.

However, a lightweight ceiling under the whole roof area with only small air inlets at either end of the hall would have many additional benefits:

- With a white painted ceiling, the light intensity and distribution in the hall would be improved.
- By fabricating the ceiling in the form of a of rock-wool sandwich, it would thermally decouple the hall from the roof, thus avoiding extreme temperatures and improving the level of comfort.
- By separating the south-west and the north-east part of the roof by a lightweight insulated partition, energy output could be increased, especially in winter.

In the present case, or when the hot air is collected directly under the roof, ventilation capacity is insufficient and should ideally be increased. Assuming, however, that collector contruction were optimised as suggested above, the present ventilation capacity should prove sufficient for buildings of similar weight and volume. This would also have some useful side-effects on hall climate and should therefore be preferred.

The time constant of the concrete storage mass (basement, ceiling and foundation) is calculated (by way of extrapolation) to be about one month.

The control system of the fans should ideally be based on measured dewpoint to prevent condensation. However:

Dewpoint control is expensive. The project showed that if the system is working correctly and is controlled only by temperature difference and relative humidity, it is possible to keep the temperature level above the dewpoint at almost all times. This would appear to make dewpoint control superfluous. However, although this system is attractive in terms of cost, it represents a compromise between number of hours below dewpoint, amount of energy transferred and season of operation.

In general, the project showed that the concept of using solar heated air to raise basement temperature and reduce relative humidity works satisfactorily. We believe there is considerable potential for such systems to heat basements used for storing a whole variety of industrial goods.

LOOE JUNIOR AND INFANT SCHOOL

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SYNOPSIS

A multi-disciplinary appraisal of a passive solar primary school in Cornwall is presented. The building was found to be energy efficient and well liked by the teaching staff. Whilst problems were noted in ventilation control and air-quality the building was considered to be a successful example of passive solar design.

INTRODUCTION

The results presented here stem in the main from monitoring carried out between January 1987 to February 1988. This paper is a summary of the detailed report submitted to ETSU [5].

Description The design of the Junior and Infant School in East Looe, Cornwall was instigated by Cornwall County Council in 1981. Working to a County Education Department general brief, which set out in some detail the spatial and functional requirements, the County Architect's department brought to the design process the desire to achieve energy efficiency whilst maintaining an architectural aesthetic. One expression of this desire was the adoption of passive solar techniques, following on from previous departmental experience in the area (e.g. St. Cleers School).

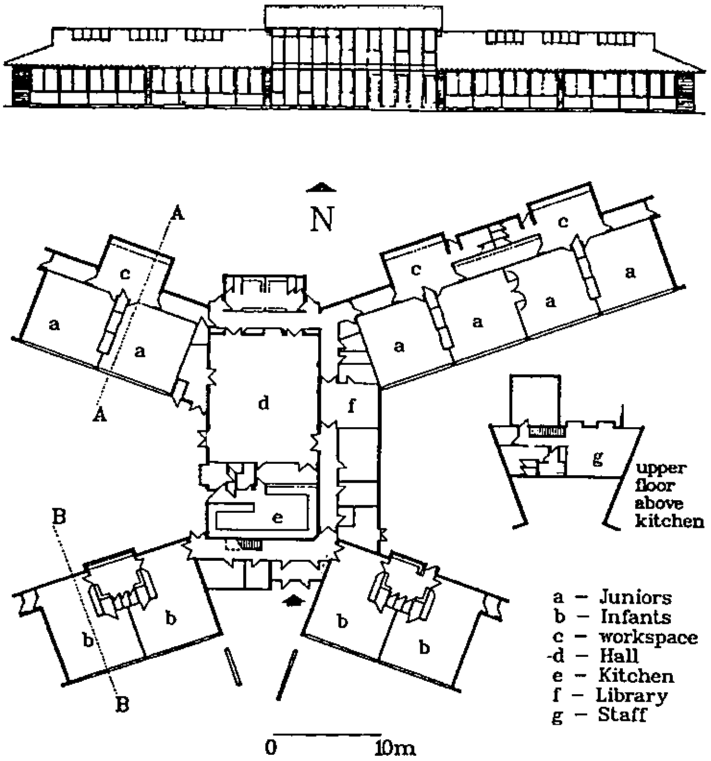
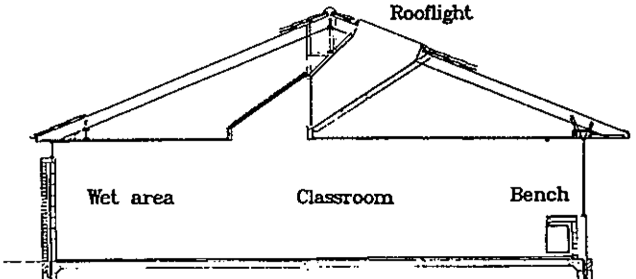


Figure 1 Elevation and plan



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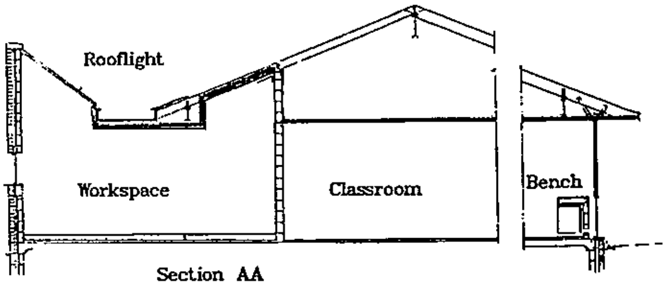

Section AA

Figure 2 Classroom sections

During the design process, the architects made use of simple design tools (for instance the RIBA calculator package) to explore fabric options, as well as the guidelines contained in the DES Design Note 17 [6]. No use was made of more sophisticated modelling techniques in the design process. The building was completed for the autumn term of 1984.

The key elements in the final design strategy became:

* a cruciform plan, orientated south as in Figure 1, to maximize the exposure to solar radiation,
* biasing of south/north glazing (71% of the total glazing area is south facing) to maximize the acceptance of solar gains,
* high levels of insulation, including double glazing to the south facades, and attention to cold bridging details in the roof space, to reduce heat loss,
* draught-lobbies and high performance glazing units to reduce infiltration losses,
* a fully glazed south facade in classrooms incorporating a short Trombe wall, as shown in Figures 2 and 3. Termed the "Trombe bench", the feature incorporates a glazed cavity, open at top and bottom, backed by a mass wall. The bench extends over the lower 40% of the glazing, to maintain the thermal benefits of 100% glazing without introducing the comfort and safety problems associated with floor-ceiling glazing.
* large overhangs (0.8m) to reduce the risk of overheating through the direct irradiance of occupants,
* thermally massive internal structures and partitions, including a quarry tile topped workbench (the top of the Trombe bench), to moderate solar gains,
* rooflights and monitors, as in Figure 2, to supplement daylight in deep areas,
* and a low lying form to reduce wind damage and heat loss.

Considerable care was directed towards providing a building that would have low running and maintenance costs. In general this meant the specification of high quality materials and construction practices.

The school has been examined in a Building Dossier (Building Magazine) [7]. A summary of the fabric and services are given in Tables 1 and 2.

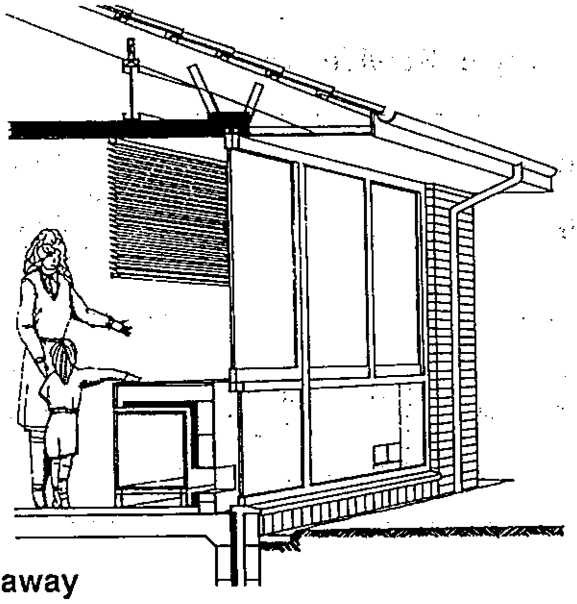

Figure 3 Trombe bench cutaway

The EPA As a result of the designer's and client's interviews the following hypotheses were specified for examination during the EPA:

- The building's energy use would be comparable to, or better than, contemporary schools.
- The building's capital cost would be comparable to contemporary schools.

- The building would be aesthetically pleasing as well as energy efficient.
- The passive solar strategy adopted would satisfy both energy and educational requirements.
- The Trombe bench would act both to reduce the incidence of overheating, and to displace heating requirements.
- The Trombe bench would maintain the benefits of 100% glazing without introducing the dis-benefits normally associated with large glazing areas.
- Infiltration heat loss would be reduced by high construction standards, without unduly affecting air quality.
- Daylight, reduced through the use of shading devices, would be adequately supplemented with that from lightwells, clerestories and roof monitors.

Table 1 Summary of Fabric Data

Opaque wall area:	658 m2	U-value: 0.43
Ground floor area:	1290 m2	U-value: 0.30
Ceiling/roof area:	1486 m2	U-value: 0.34
Window area:		
(double)	259 m2	U-value: 4.00
(single)	77 m2	U-value: 7.00
Rooflights area:		
(double)	73 m2	U-value: 4.00
Gross floor area:	1374 m2	
Floor perimeter:	266 m2	
Floor-Ceiling height	2.4 m2	

Table 2 Summary of Services Data

Space heating capacity (output)	149 W/m2 GFA (in 3 modules)
Hot water capacity:	35 W/m2 GFA
Lighting capacity:	12 W/m2 GFA
Target ventilation rate:	2.4 ac/h
Ventilation loss coefficient:	2.2 W/ C/m2 GFA
Fabric heat loss coefficient:	2.2 W/ C/m2 GFA
Design Day heat loss:	84 w/m2 GFA

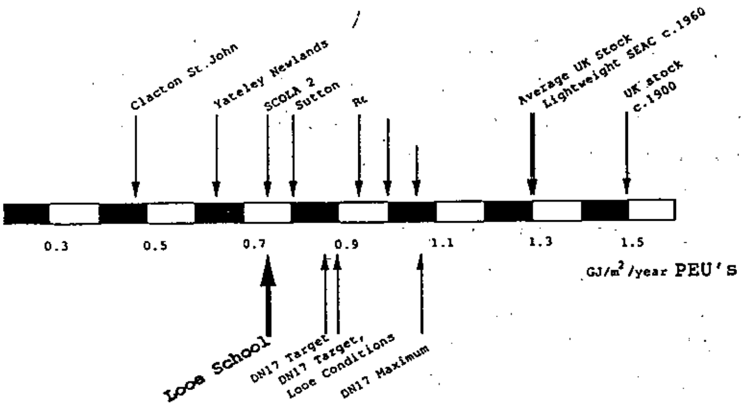

Figure 4 - Annual energy use comparators.

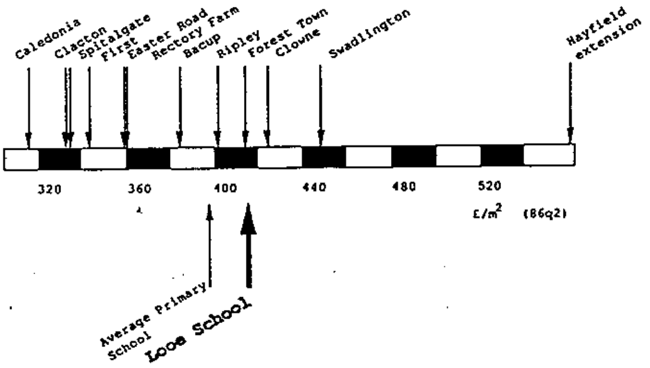

Figure 5 - Capital cost comparators.

Core Results

Energy. The school's annual fuel use was comparable to that of contemporary energy efficient school designs (Figure 4), some of which utilized "High-tech" options such as ventilation heat recovery, or heat pump systems. The reference examples were taken from recent publications and from the BMCIS database on energy use in buildings [8]. At 0.75 GJm-2/annum, the school bettered the Audit Commission "yardstick" of 0.9 GJm-2 for energy efficiency in schools.

Note that, because of the case study approach the temptation to subtract one figure from the other (i.e. passive solar - traditional) and pronounce a "percentage saving", must be resisted.

Cost. The capital cost at £417/m2 (base date - 2nd quarter 1986) was higher than that of the current average primary school adjusted to the same date, £398/m2 (Figure 5). Cost references were found in recent publications (i.e. Building Dossiers), and in the BCIS database on construction costs [9]. The range of primary school cost was found to be £208-£610/m2, with 75% of schools falling below £445/m2. It was felt that the apparent extra cost involved in Looe School was not significant, and that the cost was therefore comparable to current practice.

Amenity. The building was well liked and appreciated by the teaching staff who considered it to be well designed and admirably suited to its function as a school. In questionnaire responses, summarized in Table 3, it scored consistently highly in most aspects of form, utility and environment.

An important aspect of amenity was the thermal environment provided within the building. With reference to overheating, which would be a concern in any direct gain building, resultant temperatures (shielded from direct sunlight) recorded in two sample classrooms over the course of the school year (excluding the out-of-term summer period) showed that high temperatures were not a chronic problem. During the school year classroom temperatures over 23 C occurred on only 8% of normal school hours (Figure 6) whilst there were only 9 recorded instances of classroom temperatures greater than 27 C. In contrast, there were some reports by teachers of overheating.

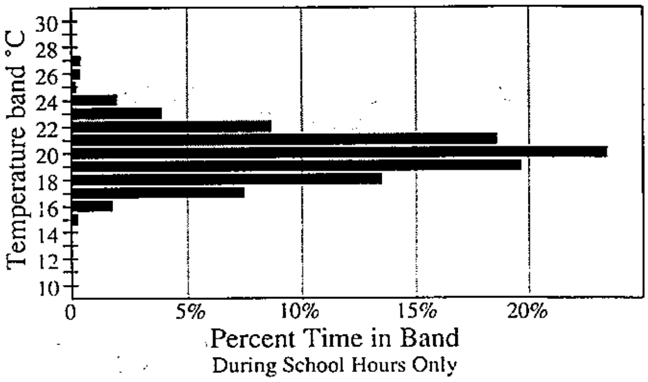

Figure 6 Classroom temperatures; time in temperature bands

	Median	Very dis-satisfied 1	2	Frequencies 3	4	Very satisfied 5
The Classroom:						
Thermal comfort in winter	4	0	0	1	4	4
Thermal comfort in summer	3	1	3	1	4	0
Ease of temperature control	2	1	4	1	3	0
Amount of daylight in winter	4	0	1	2	5	1
Amount of daylight in summer	4	0	1	3	3	2
Decoration	4	0	0	1	7	1
Character and "atmosphere"	4	0	1	0	4	4
Air quality	2	2	3	2	2	0
Visual appearances inside	4	0	0	0	5	4
Suitability for the job	4	0	0	1	4	4
Layout and design	4	0	0	2	3	4
Soundproofing from other rooms	4	0	0	3	3	3
Soundproofing from outside noise	4	0	0	1	5	3
Extent of the view of outside	4	0	1	1	4	3
Spaciousness	4	0	1	0	6	2
The *Classroom* overall	4	0	0	1	7	1
The Building:						
Standard of construction	4	0	0	2	5	2
Appearance viewed from the rear	4	0	1	1	6	1
Appearance viewed from the front	4	0	0	0	5	4
The *Building* overall	4	0	0	1	6	2

(N = 9)

Table 3 Satisfaction with Aspects of Environment

Detailed Investigation

Disaggregation. Sub-metering was used to determine to what uses the fuel energy had been put. Figure 7 shows the school's annual energy use breakdown. As might be expected this was largely biased to space heating, an area where energy savings are potentially great.

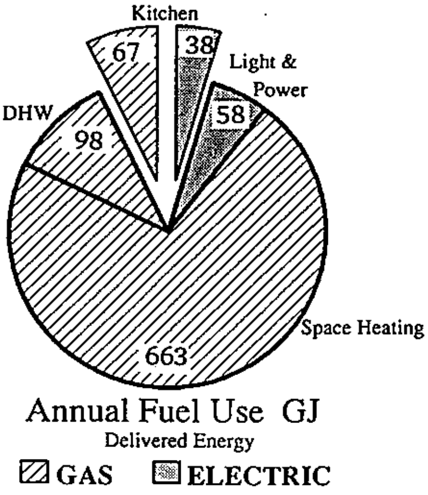

Figure 7 Desegregated annual fuel use

Response to Solar Gains. While the EPA trial does not attempt to measure a marginal passive solar energy saving over some notional "standard" school building, it was important to demonstrate whether the building had utilized solar gains. The data collected in Looe School shows this in two ways: in the free floating response of internal temperature, and in the long term response of fuel use to changing climate. Figure 8 shows the response of an unoccupied, unheated classroom (during a weekend) on a clear, sunny day in November. In comparison to a deep corridor area, there was a considerable temperature gain of approximately 7 C by mid-day. This was considered to be mainly attributable to direct solar gains.

For this incoming solar energy to be useful in displacing space heating fuel required an appropriate response by the school's heating system. Figure 9 shows the correlation found between weekly heating fuel use and weekly solar irradiance (n.b. the strong correlation between heating and external temperature has been removed by regression, this graph displays the residuals after that correction). The correlation of 0.75 is good, indicating that the building/heating system was indeed responding to solar gains.

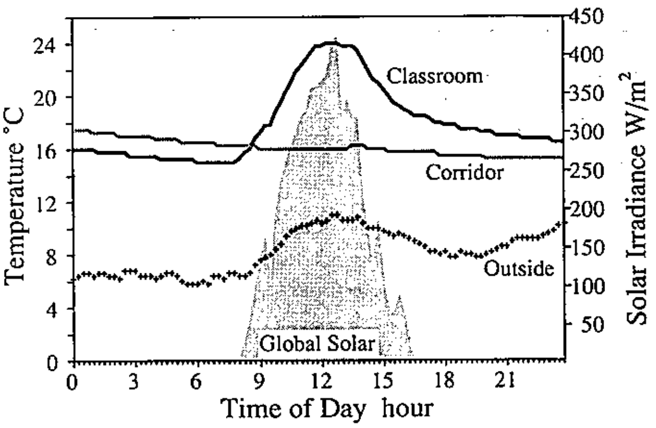

Figure 8 Free-floating response to solar gains

The average weekly solar irradiance over the school heating season was 0.06 GJm-2. From the preceding result, the average reduction in heating requirement (beyond the case of no solar gains) can be estimated as 6.4 GJ/week, or some 40% of the measured average space heating requirement of 16.2 GJ/week. Obviously from the scatter apparent in the data of Figure 9, this is not a precise estimate of the solar gains, but it does provide a useful indication of the order of the solar response.

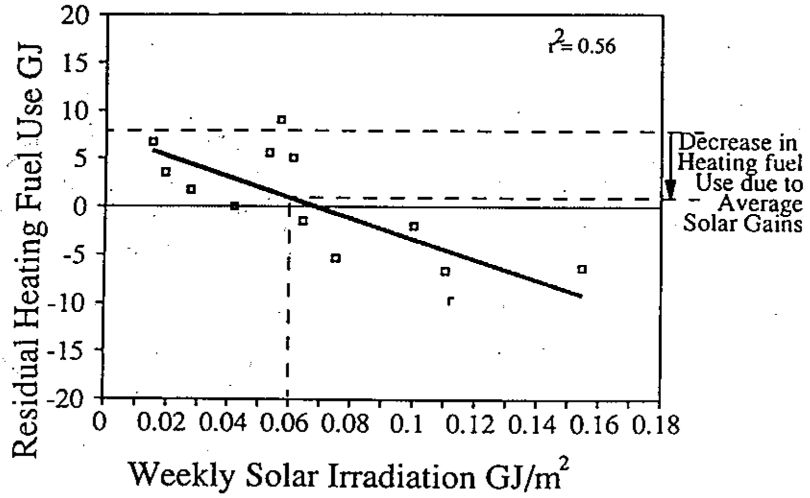

Figure 9 School heating response to solar gains

Overheating risks. The risk of overheating may overshadow any energy savings. The physical monitoring indicated that there should have been little problem with high internal temperatures in the classrooms. The occupant study showed however, that overheating was often perceived. Summer overheating was the aspect of the school which generated the most complaints to the operators (Table 4).

Table 4 Causes for complaint

Issue complained about	Number of Complaints In past year	Number of Complainants In past year
Classroom being too hot	23	4
Classroom being too bright	12	2
Some other aspect of the classroom	12	2
Classroom being too smelly	10	1
Classroom being too cool	8	2
Environmental conditions being uncontrollable	2	1
Classroom being too dark	0	0
Classroom being too noisy	0	0

(N = 9)

This contradiction between physical and human factors findings was thought to be due to several factors. Firstly, high temperatures were thought to occur in some areas outside of the classrooms, which were not monitored. In particular, complaints were received about the top-lit spaces to the rear (north) of the junior rooms.

Secondly, that which is measured physically is not always an adequate indicator of the conditions perceived by the occupants. In particular, the effect of direct solar irradiation on comfort conditions was not taken into account in the core measurements. These, as is generally the case, were made in a position to the rear of the classroom so as to avoid direct sight of the sun at all times. The students and teachers would not always have that freedom, and in an otherwise comfortable environment, the heating effect of even a short exposure to direct solar gains would cause thermal discomfort.

The avoidance of such direct exposure is a function of shading, but with any south facing glazing there is the possibility of exposure at critical times of the year or times of the day. Figure 10 shows the difference in temperature between the deep shaded location and one sited at the teacher's desk, sited near the window. It can be seen that there was a peak in the early morning, thought to be caused by a direct sight-line to the sun. This "window" of direct view was quite narrow, and it would be difficult to reduce this further through external shading, without radically affecting daylight levels and the occupants' feelings of contact with the outside. The problem should have been countered by the use of the internal venetian blinds, which had been provided for this purpose. These however, because of their interference with display items on the window bench, were not always used to their full advantage.

Finally, the perception of overheating is a function of many factors. In particular it may be complicated by non-thermal issues such as air-quality, stuffiness, odour and humidity. Certainly air quality was found to be an area of concern, both in human response and physical measurements.

It was considered therefore, that the overheating reported was not critical in the overall performance of the school, and apart from the junior work areas beneath the rooflights, was not directly attributable to the "direct gain" nature of the design.

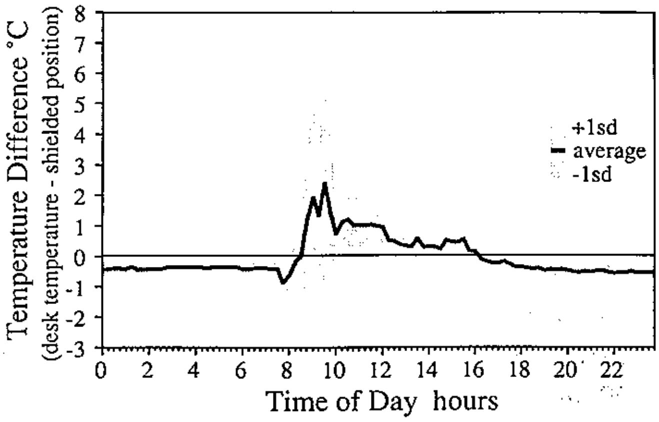

Figure 10 Temperature difference between shielded and exposed positions.

Ventilation, Windows and Air Quality. As part of the design intent, infiltration rates were to be kept low. The designer believed that sufficient supply of fresh air during occupation, would be provided through door and window opening and the regular movement of pupils in and out of rooms.

During a period of intensive testing in November 1987, the overnight decay of internal CO2 level indicated that infiltration rates were indeed low, approximately 0.25 AC/hr (Figure 11). In some instances the CO2 level was not reduced to the outside background level by the start of the next school day. While there is no suggestion that CO2 in itself poses an environmental problem in the quantities observed, metabolic CO2 levels are generally accepted as a good indicator of body odour [10]. The test results would seem to indicate that although a "tight" envelope had resulted in low infiltration rates, there was likely to be a growing odour problem during weather conditions where windows could not be satisfactorily opened during the day.

This was supported by the occupant survey which showed that poor air quality was one of the major concerns of the staff. Air quality was one of the few issues to receive an unfavourable rating (Table 3).

Records of CO2 levels made during school hours were used to provide an indication of ventilation rates during occupancy. This could not be precise due to the lack of accurate data on the numbers of pupils, and their metabolic rates, in the classroom during the monitoring period. The average concentration observed during room use was approximately 1600 ppm. Assuming 30 pupils each producing 12 l/h CO2, this indicates an average ventilation rate in the region of 3 air changes per hour. This is close to the design value suggested by the DES guidelines (2.4 AC/hr).

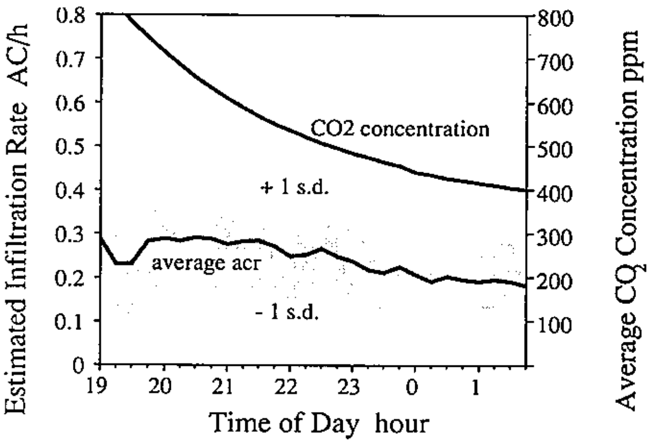

Figure 11 Average overnight infiltration

However, a closer investigation of the wide variance observed indicated that CO2 levels were bimodal. There were protracted periods of distinctly different regimes which were either quite high (>2000 ppm, suggesting low ventilation rates in the region of 1 air change per hour) or quite low (<600 ppm, suggesting high ventilation rates in the region of 10 AC/hr) as shown in Figure 12. The distinguishing characteristic between these regimes was in the use of the windows; the higher ventilation rates occurred when windows were open, the lower rates when they were closed.

The sensitivity observed (approximately 1 to 10 in ventilation rate) is felt to be a function of the frame type in use. The horizontally sliding units would have provided a large open area even when opened by only a small amount. On an exposed, windy site this would effectively reduce the teachers' control over ventilation and air quality. Table 5 shows the response by teachers when asked about their ability to control aspects of their classroom environment. As might be expected, control over air quality received the lowest rating.

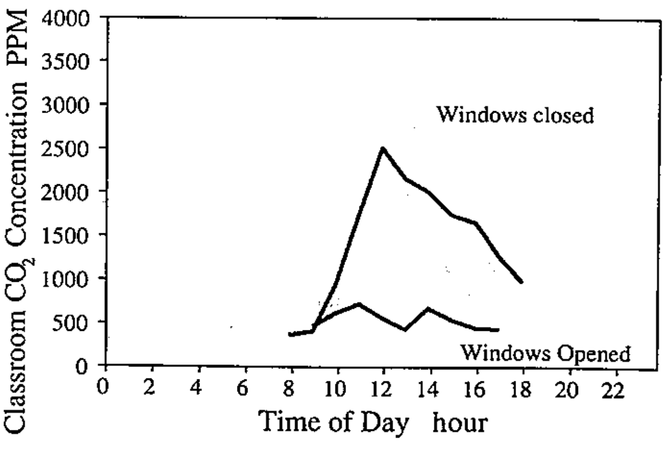

Figure 12 CO2 levels during school days

Trombe Bench. The bench was designed to act in four main areas. Firstly, the bench top was to store incoming solar energy and delay its release to the classroom, so as to reduce overheating due to direct gains. Secondly, the glazed open-topped cavity was intended to warm and circulate room air, providing solar space heating. Thirdly, the bench top was to provide a useful work and display surface for the classroom. Fourthly, the bench by its size and location was to provide a safety and comfort barrier between the pupils and the floor to ceiling glazing.

From the measurements made this feature could not be adjudged a success. While no direct dis-benefits were noted, it was found to have limited amenity appeal and to make only a minor contribution to the building's energy performance. The safety aspects of the bench were however unchallenged.

Measurements of worktop temperature and heat fluxes indicated that solar energy was stored in the tiled surface for later release as convective heat. The relatively small area and mass of the feature meant however, that for the temperature rises observed only approximately 1 kWh was stored per classroom on a sunny day. It can be estimated that this would account for less than one degree Celsius reduction in peak classroom air temperature.

The second effect also occurred in practice. Under suitable (i.e. sunny) conditions, air warmed by solar gains was found to rise from the cavity into the classroom, as in the third diagram of Figure 13. Again however, the energy flows involved were small compared to the estimated total energy flow in the classroom. The heat "output" of the cavity was estimated as 2 kWh per classroom on a sunny day, under the same conditions, direct gains of some 20 kWh might have been expected through the remainder of the window.

Occupants' satisfaction with their control over:	Median	n	Very Dis-satisfied 1	2	Frequency 3	4	Very Satisfied 5	N who said Condition never occured
When it becomes too cool	4	8	1	0	2	1	3	1
When it becomes too bright because of the sun	4	9	1	2	1	5	0	0
When it becomes too warm because of the heating	3	9	1	2	3	2	1	0
When it becomes too warm because of the weather	3	9	2	2	3	2	0	0
When it becomes stuffy or smelly	2	9	3	2	2	2	0	0

Table 5 Satisfaction with control over environment

The designer made no provision to restrict down-draughts off the windows from entering the cavity to cool further and then be injected into the classroom at floor level. This flow pattern (first diagram of Figure 13) was observed during cool cloudy days. However, there were no occupant reports of discomfort from cold draughts at floor level.

Often during the monitored period, temperatures in the cavity suggested the existence of a third flow pattern. Whilst the cavity was hot the temperatures at the outlets and inlets were low, suggesting that there was no net movement through the cavity. A site visit did not coincide with one of these periods, so that this effect was not directly observed. A simulation exercise, using a computational fluid dynamics mode

(PHOENICS, from CHAM), confirmed that under moderate conditions the cool down-draught off the windows opposed the warm up-draught from the cavity, effectively trapping the solar energy in the cavity construction.

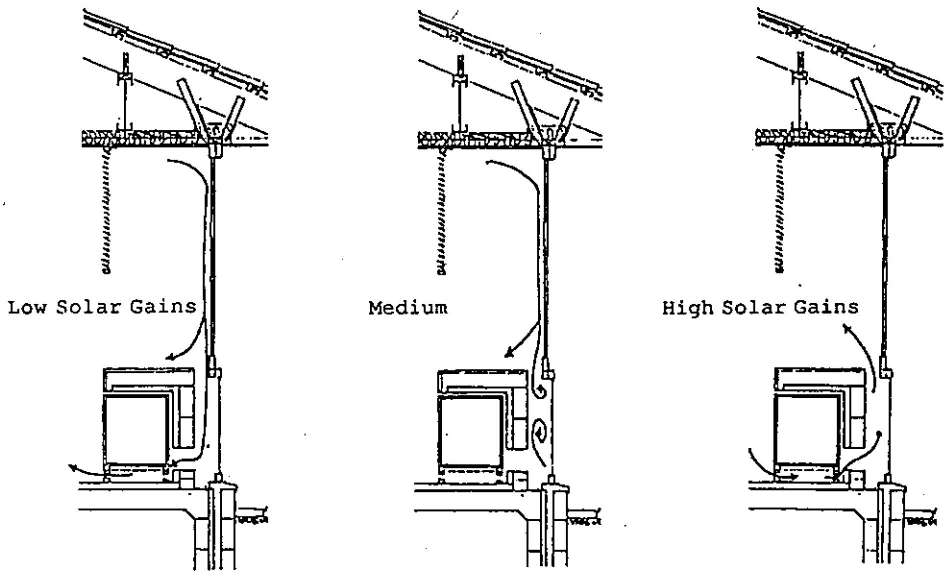

Figure 13 Air flow patterns in Trombe bench

There was a further conflict arising from the positioning of the Trombe bench under the openable windows which was felt to have limited the feature's effectiveness as a solar collector. This conflict arose at those times when the cavity would have been at its most effective, i.e. during sunny days. This would also have appeared to have been the times when the windows were opened to increase ventilation. Figure 14 shows the interaction of the cavity with the openable windows. As the windows were opened the trapped heat and elevated cavity temperature were very quickly lost. It is these elevated temperatures that are required to promote a buoyancy flow upwards from the cavity into the classroom.

As a worktop, the feature was not appreciated by the teaching staff, mainly due to the difficulties associated with display materials being disturbed when windows were open, and with the interference with the display items by the venetian blinds when they were lowered. As seen in Figure 3, the blinds were mounted at the internal edge of the bench top. This was so as not to effect the solar performance of the worktop, but the positioning effectively cancelled the utility of the worktop as a display area when the blinds were required.

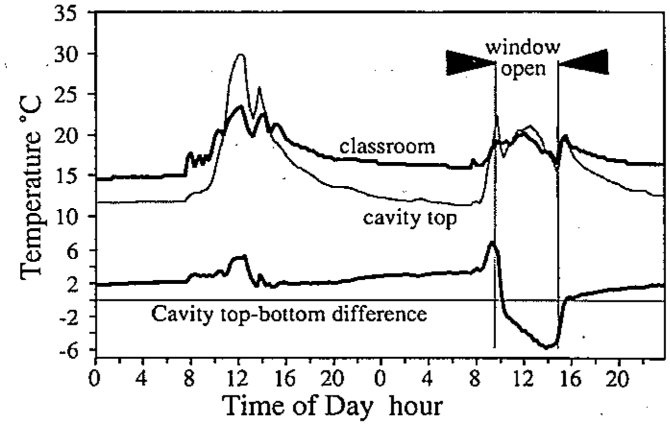

Figure 14 Interaction between cavity temperature and window use

Cost Implications. In the costing procedure, little extra cost was attributed to the passive solar design features. In general the envelope costs were higher than was considered normal in primary schools. This could largely be attributed to the use of double glazing, and to the high insulation levels specified. These higher fabric costs were offset somewhat by advantage being taken of the energy efficient design. The low heating requirement meant that a small (and therefore low in cost) heating system could be used.

Daylight. A number of teachers expressed disappointment at the level of daylight in the classrooms, particularly in view of the large glazing areas provided. The daylight levels were expected to be effected by the large overhangs provided for solar shading. However, the lightwells and roof monitors incorporated in the design to counteract this effect were not overly successful. The rooflights in the junior work spaces were rather too effective, producing very high daylight levels and associated glare. In the infants' rooms (Figure 15) they would appear to have maintained an even daylight level to the back of the room, but as the average daylight factor at desk height was less than 2% the daylight feature would have made little impact on the use of artificial lighting.

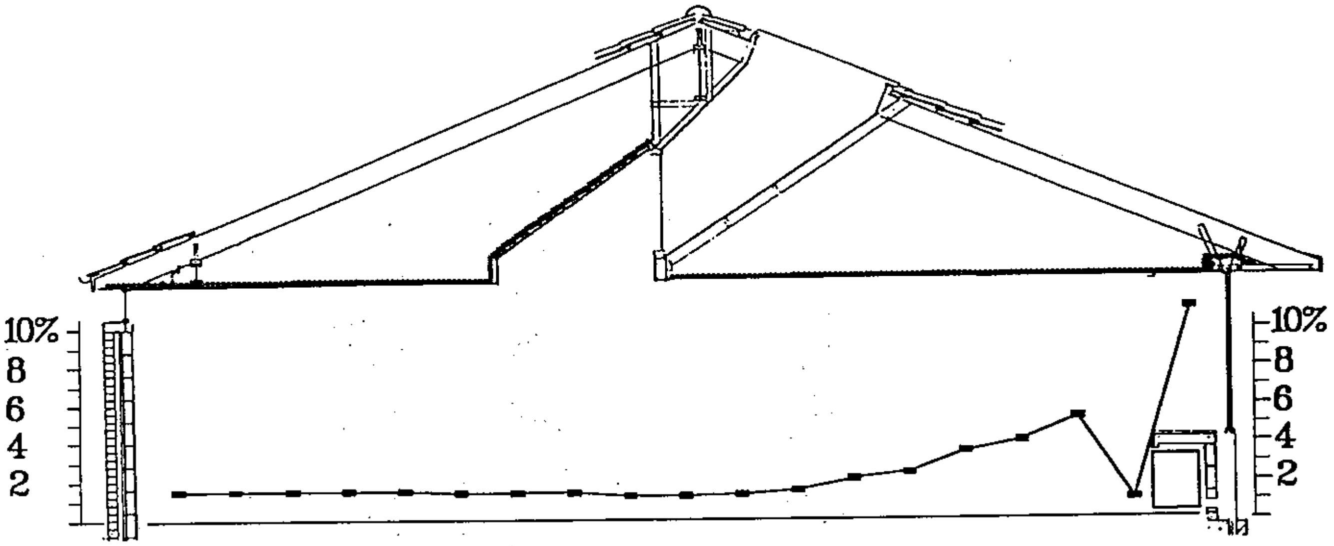

Figure 15 Daylight Factors (%) in Infants classroom section

Teachers' Perceptions of the School. A detailed amenity study, based on questionnaires and semi-structured interviews, was undertaken into the teachers' perceptions of their school, and their classroom in particular. As the median scores in Table 3 show, teachers were satisfied with most aspects of their built environment. This is further supported by the semantic differential scale evaluations summarized in Figure 16. The measures were repeated with an intervening period of 19 months. There was little difference in the result, indicating that the results are not based on a short term reaction to the "newness" or novelty of the building.

The teachers were generally complementary about the school making comments such as:

"Apart from that (overheating), the building is still very pleasant to work in. Going round to other schools this is a very well designed and a very pleasant building to work in. And I do still think (after some eighteen months of occupation) that it has some effect on the children to come into an environment that

is well designed and well planned, and calming in a way and pleasing to work in. I think it has a good effect upon everyone, it is still a pleasure to come here to work."

"It's healthier, much healthier. I haven't had any colds or things like that to complain of in the last eighteen months. Which is marvellous, when you think that I used to have 3 or 4 colds a winter (in the previous school)."

"Oh, they (the children) love it, they think it's heavenly to be in here. I mean I've got two boys who came to me this week and they can't get over the building. I can't stop them because they go on raving about it. Visitors are the same, they keep envying us - 'What a splendid view' and 'What a magnificent building you have'."

"I get a great deal of enjoyment from working in this building, a great deal of fulfilment from working in this building...it is a welcoming place to come to. I'm pleased to come back into it if we have had a holiday. The frustrations that one feels are no different from the frustrations that there would be in any other school. Maybe they are slightly less by the fact that I regard the environment as I do. Pride, happiness, enjoyment, satisfaction and fulfilment are all emotions that I experience in the course of a week working in this building. Frustration (as well), if you attempt to do something and can't."

Finally, the headmaster has stated:

"The facilities provided are second to none. I've described it before, as a school that works - a building, I mean, that works."

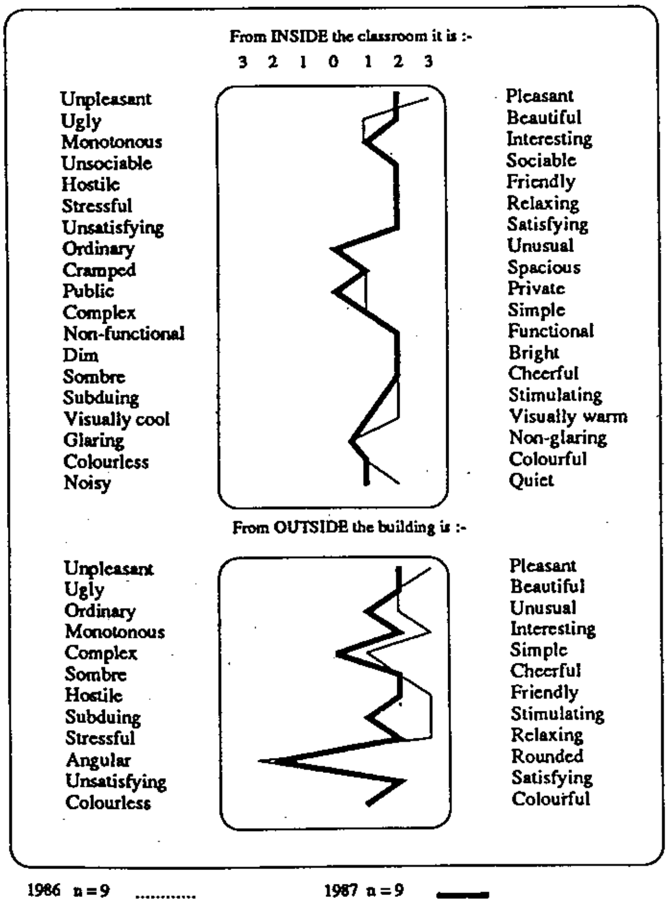

Figure 16 Occupants' descriptions using semantic differentials

CONCLUSIONS AND OVERALL ASSESSMENT

Although in this sort of work there can be a tendency to focus on negative aspects, it must not be lost that overall, in energy, amenity and cost terms, the building has been demonstrated to be a success. As a "low-tech" solution, it is felt to provide a good example of successful passive solar design. It has shows that a direct gain strategy can, with sufficient attention to shading and control, provide a satisfactory environment in schools whilst producing energy benefits.

In summary:

* The building's energy use was comparable to or better than contemporary schools.
* The building's capital cost was comparable to contemporary schools.
* The building was found to be aesthetically pleasing and energy efficient.
* The building satisfied both energy and functional requirements.
* The built environment was generally found to be satisfactory.
* The building (and its heating system) responded positively to solar gains.

However,

* The Trombe bench was not found to be a significant contributor to the building's overall energy performance. The building's solar response type was thought to be primarily direct gain.
* The Trombe bench did not introduce any apparent dis-benefits, and so it could be considered to be at least as effective as the equivalent area of simple glazing.
* Overnight infiltration rates were very low. They were perhaps too low, as there were several indicators of odour problems in the classrooms.
* Control over ventilation during occupancy was difficult, further contributing to air quality problems.
* There were some reports of overheating, although physical temperatures were not high. The reports were felt to rise mainly from periodic direct heating by sun-beams, though this was as well controlled as could be expected, given the glazing area provided.

The negative aspects of the performance highlighted here (i.e. the conflict between the positioning of the bench and windows, the type and amount of openable window, or the effect of even slight exposure to sun-beams) underline the subtleties involved in Passive Solar design. The juxtaposition of strategies, that individually should work, without detailed consideration of their interactions can lead to conflicts in operation, which can either defeat the intended benefits or introduce unanticipated effects.

The level of subtlety operating in passive solar buildings reinforces the need for a strong knowledge base of case histories reflecting the range of circumstances in the UK. Furthermore, it demonstrates the need for relatively simple design tools that enable designers to predict the effects of interactions between individual strategies.

ACKNOWLEDGEMENT

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